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ANOMALOUS WARMING OF THE STRATOSPHERE OVER NORTH AMERICA IN EARLY 1957

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ABSTRACT

The anomalous stratospheric warming of January and February 1957 is studied in detail by means of constant pressure charts, time sections, and cross sections. The warming occurred as the meandering Arctic stratospheric jet stream of wave number two developed into a pair of vortices extending to above the 10-mb. surface. It is concluded that development of stratospheric waves in the Northern Hemisphere is facilitated by autumnal growth of a forced perturbation locked in place by a warm ridge over the Aleutian area. The baroclinicity and rate of development were in agreement with Fleagle's criteria for the growth of disturbances. Interaction between the tropospheric jet stream and Arctic stratospheric jet stream during the period of development is believed responsible for the great intensity of the 1957 warming.

1. INTRODUCTION

For the meteorologist familiar with the synoptic charts of the lower levels, the annual course of events in the upper stratospheric layers,[1] as represented by constant pressure analysis of surfaces between 50 and 10 mb., is a fascinating one to follow. During the summer months, when temperature increases from equator to poles, east winds that increase with height blow in almost complete isolation from activity in the lower stratosphere and troposphere. In September and October [27], winds with westerly components appear first in high latitudes and then progressively southward into the subtropics. The troughs and ridges of the upper stratospheric westerlies generally conform with the major troughs and ridges of the troposphere and are influenced little by minor tropospheric waves. However, during the coldest part of the year, traces of strongly developing systems may appear at the 50-mb., or rarely at the 25-mb., surface, although with marked westward tilt and with amplitude greatly reduced particularly above the southern portion of the tropospheric disturbances. Many of the relationships and differences between stratospheric and tropospheric circulations were first described by Austin and Krawitz [1].

Within the Arctic Circle, the gradual lowering of temperature during the first months of the long polar night is accompanied by formation and intensification of the Arctic stratospheric jet stream in the baroclinic zone between the cold Arctic core and the warm zone that almost completely encircles the earth above the tropopause in higher middle latitudes. The speed of this jet stream quite regularly reaches 100 knots and occasionally exceeds 200 knots.

A large increase in amplitude of waves in the Arctic stratospheric jet stream and accompanying deterioration of its cold core have been observed to occur quite suddenly at some time during the first 12 weeks of the year, but there have been insufficient analyses of the 50-mb. and higher surfaces for the past years to reveal all of the necessary stages in the life history and other general characteristics of the Arctic stratospheric jet stream. The

[1] Herein, the stratosphere will be considered as the layer from the tropopause up to the stratopause. In middle latitudes this layer is nearly isothermal. The stratosphere is divided into the upper stratosphere, approximately from 35 km. down to 20 km., and the lower stratosphere, from 20 km. down to the tropopause. In contrast to the upper stratosphere, the lower stratosphere exhibits strongly many of the minor trough and ridge features of the troposphere. In upper stratospheric troughs and ridges, contours and isotherms are generally in phase while in the lower stratosphere contours and isotherms are usually out of phase. Above the stratopause is the thermoincline of the ozonosphere or chemosphere in which temperature increases with height up to a maximum somewhere near the 50-km. level. The stratopause at low latitudes is indistinct since the tropical stratosphere is also a thermoincline, while at high latitudes, in winter, its nature is unknown.

most spectacular phenomenon associated with the amplification of waves in this jet stream has been anomalous warming of the upper stratosphere. Scherhag [17] reported an instance of this type of anomalous warming in 1952 and referred to it as "explosive" warming. Possibly because the large scale of the phenomenon in process was not fully appreciated, a solar origin for the warming was proposed by some writers. Following further documentation of warming epochs, Wexler [29, 31] found that little if any convincing evidence of a solar origin could be brought forth and that the observed warming could in each case be explained by subsidence and the adiabatic heating of air descending from potentially warmer layers. The possibility of a trigger action by solar activity still remains since the polar stratosphere seems to build up in the winter season to a condition of baroclinic instability and not all of the factors capable of releasing the instability and producing associated phenomena like anomalous warming are known.

The stratospheric warming of 1957 is perhaps the most spectacular of those reported on to date. It certainly lends itself to closer examination than those that occurred previously because of its initiation in middle latitudes over North America and subsequent passage over many excellent radiosonde stations and because of the exceptional magnitude of associated features such as wind speeds and temperature changes. Craig and Hering [2] presented selected charts from their series of daily 100-, 50-, and 25-mb. charts to show the changes that took place at one week intervals between January 23 and February 20, 1957. Godson and Lee [6] discussed developments in this same period and for analogous periods in the two previous winters by means of vertical cross sections and time-altitude charts. Even so, these complex motions of the atmosphere have not been completely explained.

Any attempt to analyze the circulation of the upper stratosphere during an entire month or season and to relate it to events in the lower layers extending down to sea level leads to a multiplicity of 2-dimensional diagrams describing sections through a 4-dimensional situation. In this paper, references to events in the lower troposphere have been held to a minimum as one means of reducing the complexity of the discussion. Many of the diagrams are composites constructed from data that have been interpolated, extrapolated, and averaged, in space or time, to minimize the effects of the sparsity and inaccuracy that are common to reports from very high altitudes. These factors were less of a problem in this 1957 case because of the large number of well-equipped stations in the region where the 1957 warming occurred and the greater heights that are progressively being attained by radiosondes.

2. SOME SOURCES OF ERROR

At this point a few remarks concerning the quality of radiosonde data are in order. These statements have been synthesized from the literature, from expert opinion, and from studies being completed by the author and his colleagues. Stratospheric temperatures are in most cases probably accurate to within 3° or 4° C. This accuracy with the U. S. Weather Bureau duct-type radiosonde in daylight flights to very great heights is obtained only by means of a radiation correction that tends to make this instrument compatible with those having a white external temperature element. Uncorrected daytime temperatures that may still be transmitted by some nations may involve very large errors at great heights. The residual diurnal variation of temperature after correction is still a burdensome complication in the analysis of time sections and other charts.

Another source of difficulty in stratospheric analysis is the pressure error. In the lower atmosphere, an error of a few millibars does not have much effect on the temperature at a level or on the computed heights of standard pressure surfaces and significant points such as fronts and the tropopause. However, at the 10-mb. surface each millibar of error causes a height error of about 650 meters in the placement of a temperature or significant point. There is evidence in the data that errors of 3 mb. are not uncommon and in a few soundings the errors appear to be much larger. The accuracy of wind calculations is affected by pressure error; the result is a wildly oscillating wind speed in cases where the pressure error is variable due to a sticking, intermittently operating baroswitch. The percentage error in calculated rate of ascent of radiosonde is nearly the same as the percentage error in pressure and for some conditions equals the percentage error in wind speed. Relatively little error in temperature and computed height is produced by the pressure error in layers with nearly isothermal lapse rate. Many of the problems that are caused by imperfect, incomplete data have been encountered and solved in summary fashion in the course of earlier stratospheric analysis projects [8, 12].

3. EVENTS LEADING UP TO THE "EXPLOSIVE" WARMING OF THE STRATOSPHERE

In January 1957, radiosonde data were being transmitted only up to the 25-mb. level on teletypewriter, and in fact at only a small percentage of stations was radiosonde equipment capable of regularly reaching that level. Thus, it was not until January 24, when large 25-mb. temperature rises were reported from Newfoundland, that the "explosive" warming of 1957 became detectable to those making use of current data received by teletypewriter. For this reason, and also because it was on that date that a well-formed, regularly-moving, warm center became established, January 24 is taken as the initial date of explosive warming. However, it will be shown below that marked warming had already been observed very high in the stratosphere at Salem, Oreg. at least 5 days earlier.

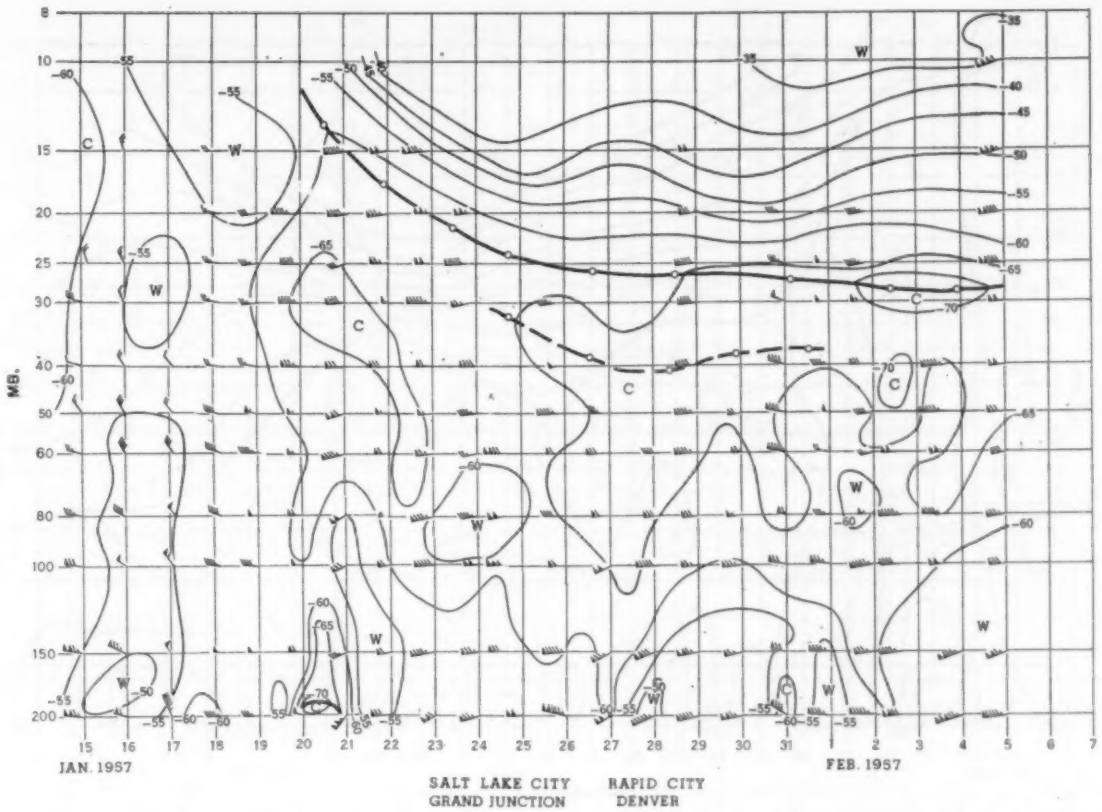

Figure 1.—Time section, January 15 to February 5, 1957, for Denver, Colo. supplemented by data for Salt Lake City, Utah, Grand Junction, Colo. and Rapid City, S. Dak. Isotherms are thin lines labelled in degrees Celsius; wind speeds are given by barbs for each 10 kt. and triangles for each 50 kt. on a shaft oriented from top of diagram for north winds. Medium line with superimposed circles indicates stratopause; line is broken to show alternative stratopause. Medium weight line without circles indicates tropopause. Vertical lines are located at 1500 GMT of indicated date. The analysis of this and other charts is carried across portions where interpolation seems justified but not into portions requiring extrapolation of data.

At the beginning of January 1957, low pressure in the upper stratosphere was centered near the North Pole, and a portion of the cold wintertime airmass of the Arctic stratosphere had penetrated southward in a trough extending from northwestern Greenland to Newfoundland and thence into the North Atlantic Ocean. At 25 mb. warm air and an anticyclone were centered over western North America. As the month progressed, cold air was advected farther into the western portion of the trough which gradually retrograded westward into central Canada. On January 12, a closed Low appeared in this trough just north of Hudson Bay. By January 18, cold air from the northwest was entering the middle stratosphere over the northwestern United States. Some of the warm air that had been associated with the anticyclone over western North America was moving rapidly eastward across the northeastern States, and the anticyclone itself had melted away into the subtropical Pacific Ocean area. Although normal contours and isotherms for the upper stratosphere have not been established, reference to daily and mean charts for and above the 50-mb. surface [1, 3, 7, 14, 23, 26] suggests that isotherms and contours at this time were very anomalous over the United States and Alaska. In comparison to the average, the temperature over parts of Alaska was 20° C. colder than usual in January. The cyclonic curvature, low temperatures, and strong westerly wind components in the northwestern United States also appear to have been anomalous.

The appearance of upper stratospheric warming on January 19 at Salem, Oreg., was first pointed out to the author in a private communication from R. A. Craig and W. S. Hering, who also described its rapid passage across the United States in the days that followed. At Salem, the reported 9-mb. (32-km.) temperature on January 19 was −48° C., an increase of 21° C. in 5 days, while at a lower altitude in the same observation a temperature of −66° C. was reported at 16 mb. (28 km.) in the southward-moving Arctic stratospheric airmass. Increasing stratospheric winds exceeded 100 kt.

Warming of the upper stratosphere and local acceleration of the wind frequently occur simultaneously with cooling of the lower stratosphere at the advancing edge of the Arctic stratospheric airmass. The lapse rate within this airmass is generally positive but very small, perhaps 1° C. per km. Above in the thermoincline there may be a temperature inversion of as much as 5° C. per km.

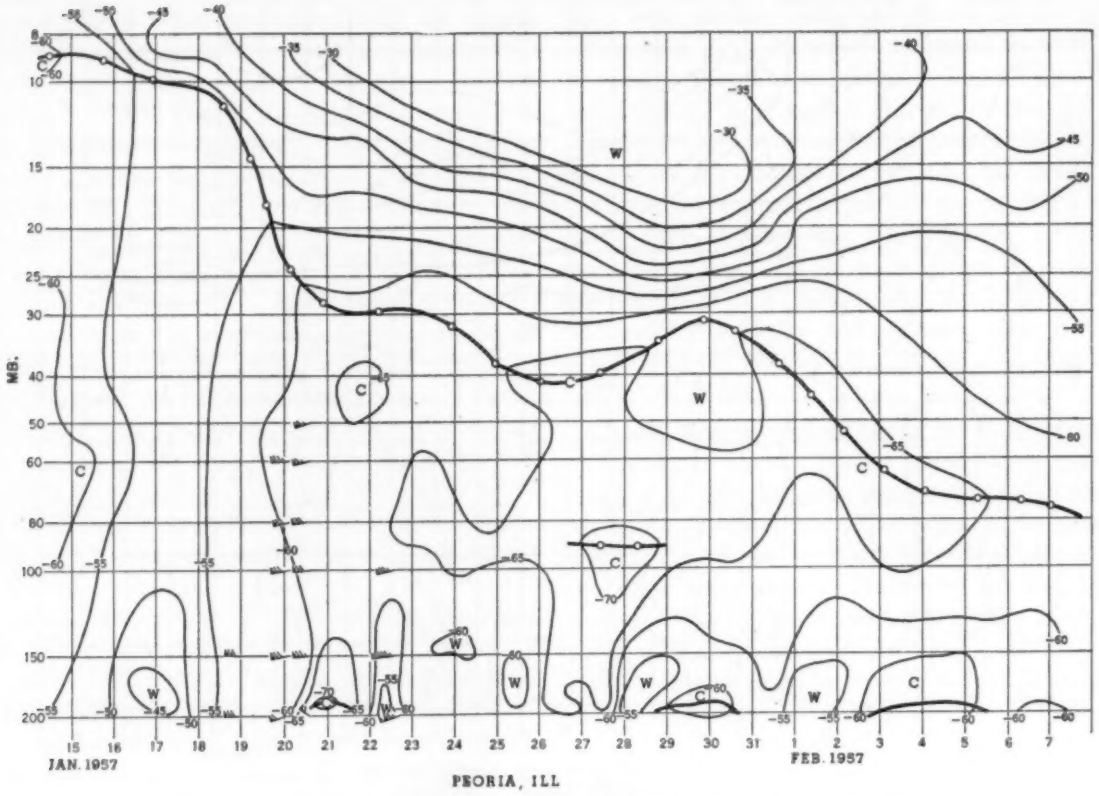

Figure 2.—Time section, January 15 to February 7, 1957, for Peoria, Ill.

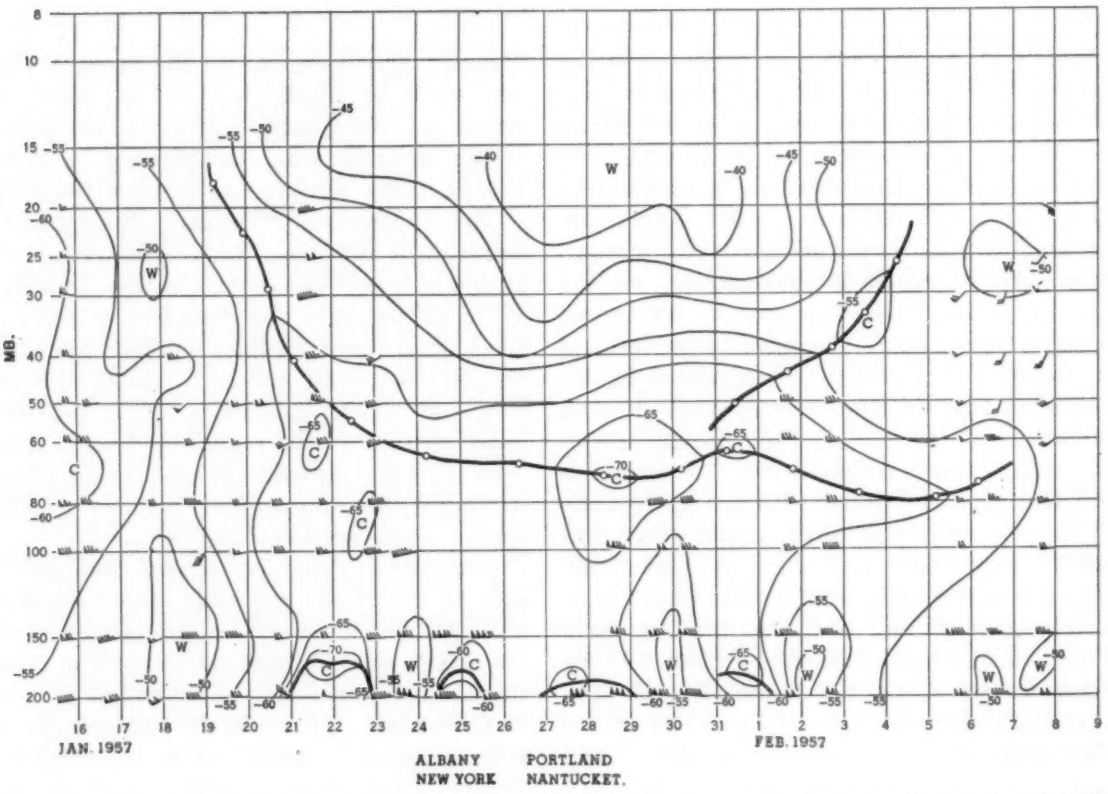

Figure 3.—Time section, January 16 to February 8, 1957, for Albany, N. Y., supplemented by data for Portland, Maine, New York City, and Nantucket, Mass.

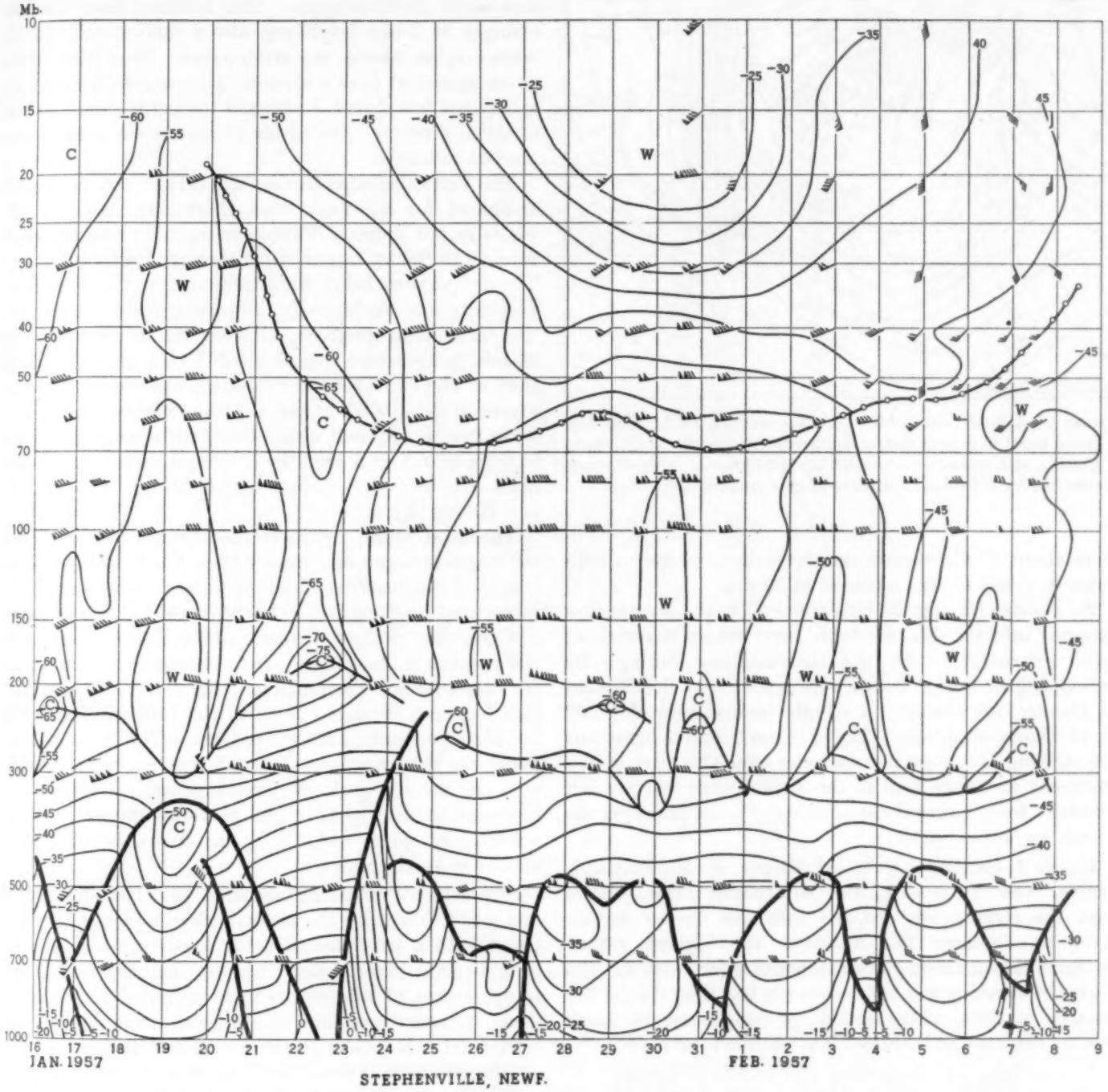

Figure 4.—Time section, January 16 to February 8, 1957, for Stephenville, Newfoundland. Analysis as in figure 1, but including frontal positions (heavy lines).

The change in lapse rate is often abrupt, forming a clearly marked boundary surface that will be referred to here as the stratopause. In this special case, the altitude of the stratopause may be much lower than usual and is analogous to the low tropopause found above cold tropospheric airmasses.

In figure 1, a composite time section for the east-central Rocky Mountain area, based primarily upon data from Denver, Colo., the stratosphere on January 19–20 cooled to below −65° C. Within 2 days, warming to −40° C. had occurred at 11 mb. and the wind speed at the high levels had increased to more than 100 kt., a high value not often observed at this altitude and latitude. The stratopause, after making its appearance below the 10-mb. surface, descended to the layer between 25 and 30 mb. by January 26. In contrast, the stratopause at Salem remained in the layer between 12 and 22 mb. from January 19 until the period February 2–6, when it descended to below the 50-mb. surface. Below the stratopause, temperatures in the Arctic stratospheric airmass at Denver

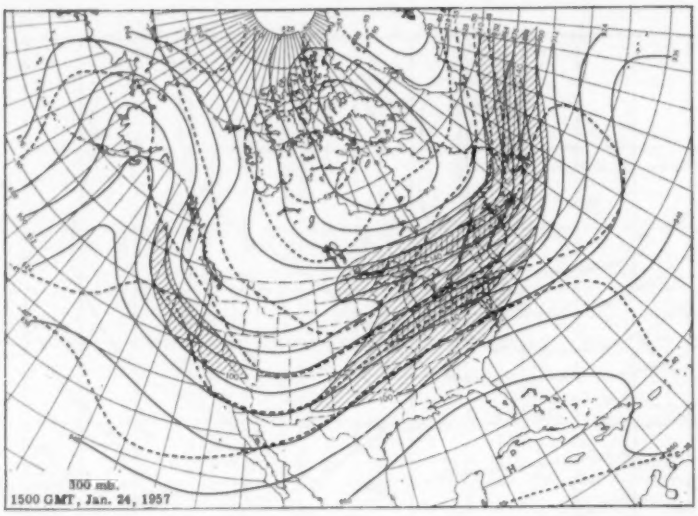

Figure 5.—300-mb. chart, 1500 GMT, January 24, 1957. Contours (solid lines) in tens of meters, isotherms (dashed lines) in degrees Celsius, and isotachs (thin solid lines) in knots. Area of winds over 100 kt. is hatched with area of maximum cross-hatched.

were about 5° C. warmer than at Salem, where on February 4, −80° C. was recorded at 33 mb.

At Peoria, Ill. (fig. 2) by January 21, the stratopause dropped into the 20- to 40-mb. layer where it remained until February 1. In the thermoincline during this period, higher temperatures were reported at Peoria than at Denver; for example, a 10-mb. temperature of −30° C. at Peoria on January 22. Figures 1 and 2 bring out the striking fact that the warming over this part of the continent was very high in the stratosphere and *was not detectable from a casual examination of temperatures at the 25-mb. surface or below.*

Figure 3, combining data for Albany, N. Y., Portland, Maine, New York City, and Nantucket, Mass., shows that the stratopause dropped into the 60- to 80-mb. layer by January 23. Although the highest valued isotherm shown above the stratopause is for −40° C., the degree of warming was not necessarily less than that at the western stations where soundings penetrated to much greater heights and therefore into warmer layers.

In searching for similarities and trends in figures 1–3, we find that a deep column of warm air associated with a mass of cold tropospheric air moving along below it moved through the stratosphere from Denver on the 16th to Albany on the 18th. Just above the 200-mb. surface a cold high tropopause appeared at Denver on the 20th, at Peoria on the 21st, and at Albany on the 22d and was surmounted by a column of cold air to a height of about 25 km. (25 mb.) at Denver, 22 km. (40 mb.) at Peoria, and 18 km. (60 mb.) at Albany. The well-marked tropopause and cold air surmounting it appeared simultaneously with a powerful thrust of warm southerly winds in the lower troposphere. That portion of the cold stratospheric air above 100 mb. was an extension of the Arctic stratospheric airmass which after its arrival remained in that region and participated only slightly in the activity at and below the tropopause. This isolation from the daily changes at lower levels was also a characteristic of the warm region above the stratopause. Once the stratopause appeared over a station, it remained at about the same level but sloped downward toward the east, so that at Albany only a thin wedge of the Arctic stratospheric airmass remained.

The vertical motion during this period can be roughly estimated for the path from Denver to Albany. The winds in the upper stratosphere were blowing at speeds from 50 to 100 kt. from Denver through Peoria to Albany. The temperature below the stratopause was fairly uniform vertically and horizontally, indicating little vertical motion in mid-stratosphere. Above the stratopause, the 25-mb. temperature was about 20° C. higher at Albany than at Denver, 1400 nautical miles upstream. With an inversion of 5° C./km., an average sinking rate of 1 to 3 cm./sec. is required along this path during the period of more than a week that the condition persisted. Higher rates occurred over shorter periods and distances (Craig and Hering [2]).

The most rapid change in the thermal pattern of the stratosphere began on January 24 in the vicinity of Goose Bay, and Stephenville, Newfoundland. Because of errors introduced by irregularities in the calculated rate of ascent of Goose Bay radiosonde observations during that period, the events are illustrated here by means of a time section for Stephenville, Newfoundland (fig. 4). This time section has been extended down to the 1000-mb. surface to include a generalized frontal pattern. The fronts did not penetrate downward to 1000 mb. in the cases of wave cyclones passing south of Newfoundland. Because time increases to the right, frontal patterns appear to be reversed, and ridges and troughs as shown by wind shifts appear to be interchanged.

Stratospheric warming occurred prior to January 20 and was followed by the appearance of a high cold tropopause with a brief incursion of Arctic stratospheric air in mid-stratosphere. Beginning on January 23, the low temperatures of mid-stratosphere modified to the more usual temperatures for this region. The stratopause settled into the 60- to 70-mb. layer, and strong warming continued above it until the 29th when a temperature of −22° C. was observed at 20 mb. Very strong winds occasionally exceeded 150 kt. during this period but decreased almost simultaneously with cessation of the warming trend.

At the commencement of the sudden or "explosive" warming following January 24, the tropospheric jet stream was unusually strong as shown by the 300-mb. chart (fig. 5). The pattern of this chart developed slowly and is quite similar to the monthly mean 300-mb. chart for January 1957 [24.] Over Canada there was a very cold Low of the type that intensifies with height up through the stratosphere, as described by Riehl [15.] A warm ridge extended northward from the Gulf of Alaska into the Arctic. Advection of cold air by the broad current of northerly winds between the Canadian Low

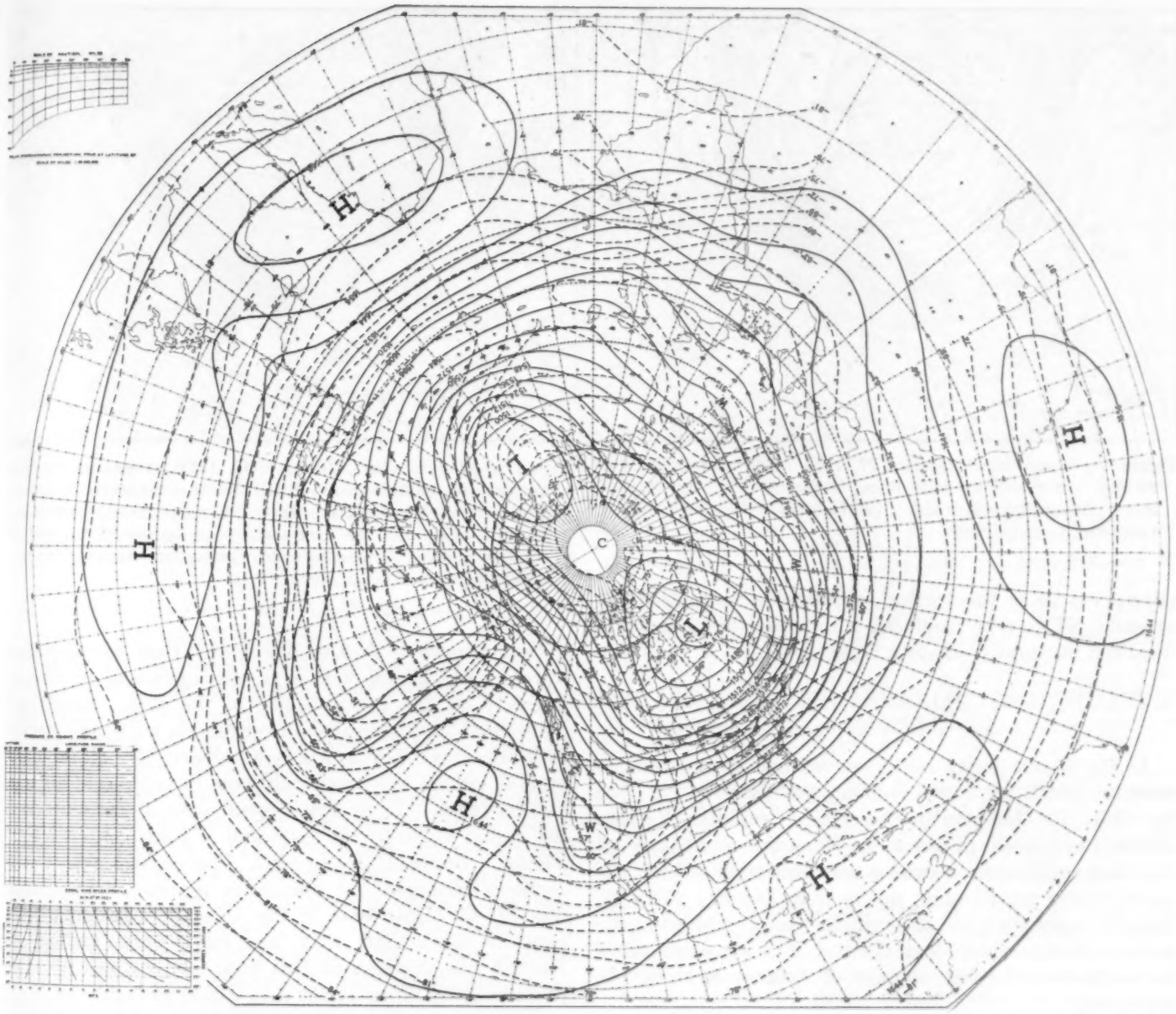

Figure 6.—100-mb. chart, January 27, 1957. Contours (in tens of meters) are shown by solid lines, isotherms (°C.) by dashed lines.

and the Alaskan ridge was an important factor in the persistence of a south-to-north temperature gradient and strong high-level westerly winds of exceptional strength across the United States. These winds accelerated as they traversed the confluence zone leading to the area of strong contour gradient between the Canadian cyclone and the ridge over Florida. The 100-kt. isotach covered the eastern United States north of 35° N., and winds exceeding 140 kt. extended in two bands from the Great Lakes to a sharp trough over the Maritime Provinces. A possible source of the kinetic energy of these winds was the potential energy released by slow settling of the inflowing cold air. In the vicinity of the sharp trough, the band of winds over 100 kt. narrowed. Since the air was moving much faster than the isotachs, it must have been decelerating and thus flowing to the right across contours.

The proposed explanation can be completed by means of reasoning used previously by Riehl and Teweles [16]. The kinetic energy released by the decelerating jet stream was reconverted into potential energy through vertical motions associated with horizontal convergence to the right of the stream and divergence to the left. In the region of divergence, the storage of potential energy can be accomplished in either of two ways, by the elevation of potentially colder air below, or the depression of potentially warmer air above, the level of zero vertical motion. Similarly in the region of convergence, the storage of potential energy may come about through the forcing of potentially warmer air downward or of potentially colder air upward. Depending upon the forces exerted in other layers, different combinations of these alternatives may predominate. Moreover, the area of maximum convergence or divergence, and thus also the area of maximum warming or cooling, may have a pro-

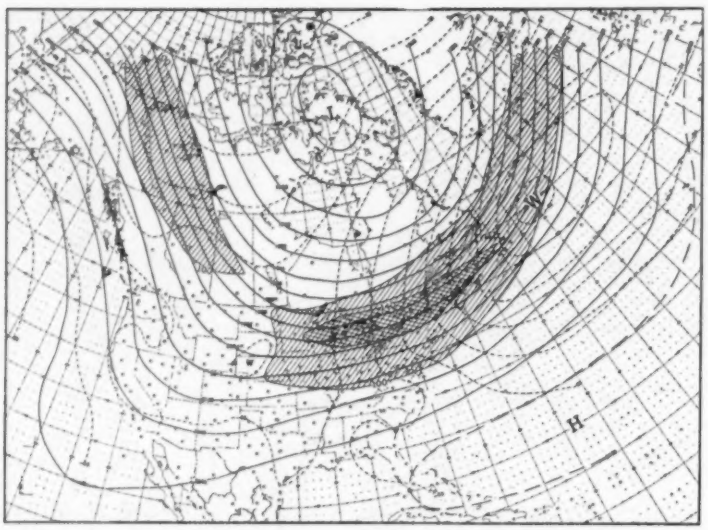

Figure 7.—50-mb. chart, January 27, 1957. Contours (in tens of meters) are shown by solid lines, isotherms (°C.) by dashed lines. Areas with winds above 100 kt. are hatched, with areas of maximum cross-hatched.

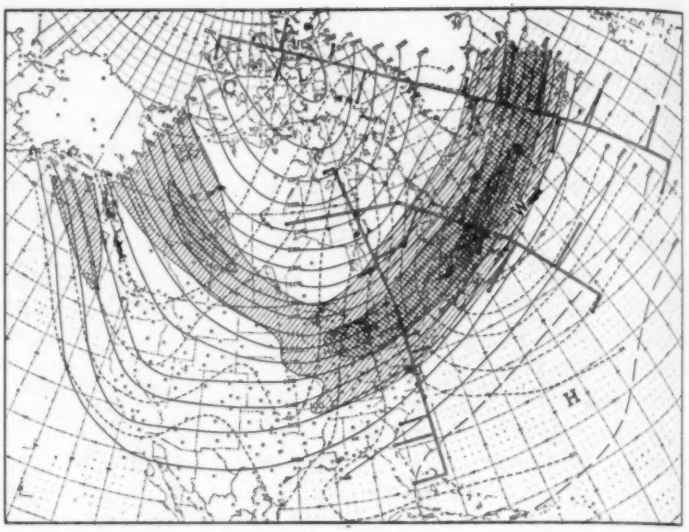

Figure 8.—25-mb. chart, January 27, 1957. Contours (tens of meters) are shown by solid lines. Isotherms (dashed lines) are means for the 50- to 25-mb. layer. Lines of intersection of the 25-mb. surface and the cross-sections in figures 10, 11, and 12 are shown, with dots locating nearby radiosonde stations. Hatching shows areas of wind above 100 kt.

nounced slope in the vertical, so that the warmest point at one level may be displaced a thousand miles or more from the warmest point at a higher level.

4. THE CIRCULATION DURING THE INTENSIFICATION STAGE

As the 25-mb. warm center moved northward from its position south of Newfoundland on January 25 (see fig. 25), its temperature increased rapidly. Various charts have been prepared to illustrate conditions at the time maximum warming was initiated. Since the warm center moved quite slowly from January 26 to 28, data for more than one observation were combined in the various charts centered at about 1500 GMT, January 27 to compensate for the scarcity of data at any one observation.

A hemispheric 100-mb. chart for January 27 (fig. 6) is presented to place events over North America in full perspective with the rest of the hemisphere. A hemispheric 50-mb. or 25-mb. chart would be preferable since the warming was more intense and clearly defined at higher altitudes, but insufficient data were available for these surfaces over Eurasia. At 100 mb., a warm center of about −50° C. was situated over the mid-Atlantic where it regenerated after moving eastward into that region on the 21st. The dual nature of this warm center is shown in the cross section from the Azores across Greenland to the Canadian Arctic (fig. 12). In the troposphere north of the Azores was the typical pattern of the polar front with its jet stream and tropopause structure. It can be seen that the warm center at 100 mb. (fig. 6) was associated in the vertical with the warm belt in the lower stratosphere north of the tropospheric jet stream, and at the same time with the strong warming of the upper stratosphere then taking place in an area centered to the northwest of this region.

From figure 6 it was discovered that a concurrent warming was taking place over stations in eastern Siberia, precisely on the opposite side of the pole. Almost all features of the phenomenon over Siberia were very similar to those over North America. Near 65° N., a deep cyclone tapped the Arctic cold pool to carry cold air into mid-latitudes. There was a confluence of contours into the region between the Low and a High centered over Burma. Between Japan and Kamchatka where the contours diverged the maximum reported temperature was 12° C. higher than in the Atlantic. Although temperature corrections may not have been applied to Russian observations at this time, the radiational temperature corrections at 100 mb. would probably be 3° C. or less. In any case, the reported temperature of −43° C. at Attu in the Aleutians substantiated the greater warmth at 100 mb. over eastern Asia.

Besides the two marked warm centers already discussed, there were at least two others at 100 mb. on January 27, one over the western United States and the other over central Europe. All four of these warm centers were situated over complex tropospheric low pressure systems, and lobes in the isothermal patterns surrounding these warm centers covered individual polar front cyclones. The effect of the deep warm layers of the lower stratosphere was to erase all trace of sea level low pressure systems from the same areas in the upper stratosphere. The two large cold, low centers that show up over Canada and Siberia on the 100-mb. chart were both located directly over the two coldest sea level areas of the Northern Hemisphere, a fact suggesting that the distribution of long-wave radiation from the surface of the earth may be a factor in determining the position of stratospheric Lows.

Conditions at the 50-, 25-, and 15-mb. surfaces in the

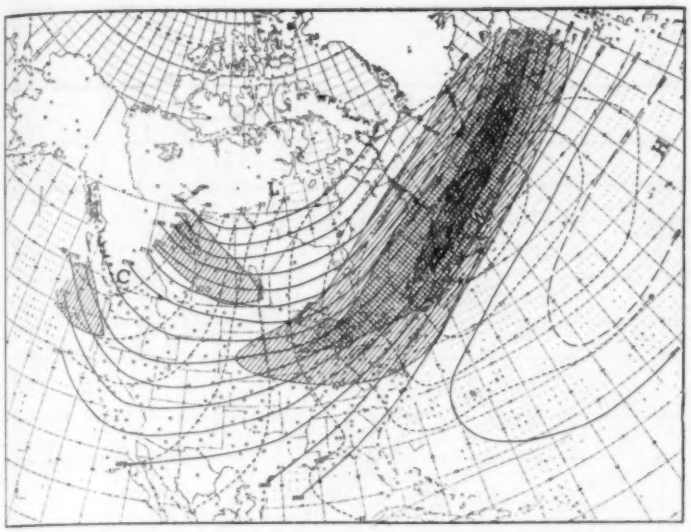

Figure 9.—15-mb. chart, January 27, 1957. Contours (tens of meters) are shown by solid lines. Isotherms (dashed lines) are means for the 25- to 15-mb. layer. Hatching shows areas of wind above 100 kt.

upper stratosphere over the North American sector on January 27 are shown in figures 7, 8, and 9.[2] The mean isotherms for the 15- to 25-mb. layer (fig. 9) show very cold air over the southwestern United States where at 100 mb. there was a warm center. On the other hand, the 100-mb. warm center over the Atlantic was surmounted by much warmer air in the 15- to 25-mb. layer. The resulting contour-isotherm relationship in the upper stratosphere agreed with the observation by Wexler and Moreland [30] that troughs of the upper stratosphere are cold in their southwest quadrants and warm in their southeast quadrants. This vertical variation of the isotherm pattern above 100 mb. also substantiates the conclusion that strong effects of vertical motion in migratory tropospheric systems extend up to the 100-mb. surface, but above that surface the motions of stratospheric systems dominate.

The westward displacement and temperature increase of the Atlantic warm center upward from 100 mb. is clearly seen in figures 7–9. Of interest also is the relation between strongest winds at the 50-mb. and 25-mb. surfaces, and the warm center in the layers above and below. In the drawing of isotachs at these surfaces, the anticyclonic shear south of the jet axis was deliberately held short of the criterion for dynamic instability even though the shear based on the construction of contours by use of mean temperature charts tended to exceed the criterion. The winds, approaching the warm center at the 50-mb. surface and in the layer below, were decelerating. Also if we assume adiabatic temperature changes, these winds descended as they moved into this region of depressed isentropic surfaces. Thus we have a current in which decrease of kinetic energy took place as the current passed through a region where buoyancy

[2] Even though almost endless consistency checks were made to overcome deficiencies in the data for these and other charts for the very high altitudes, inaccuracies probably remain, and reliance should not be placed in minor details and small differences.

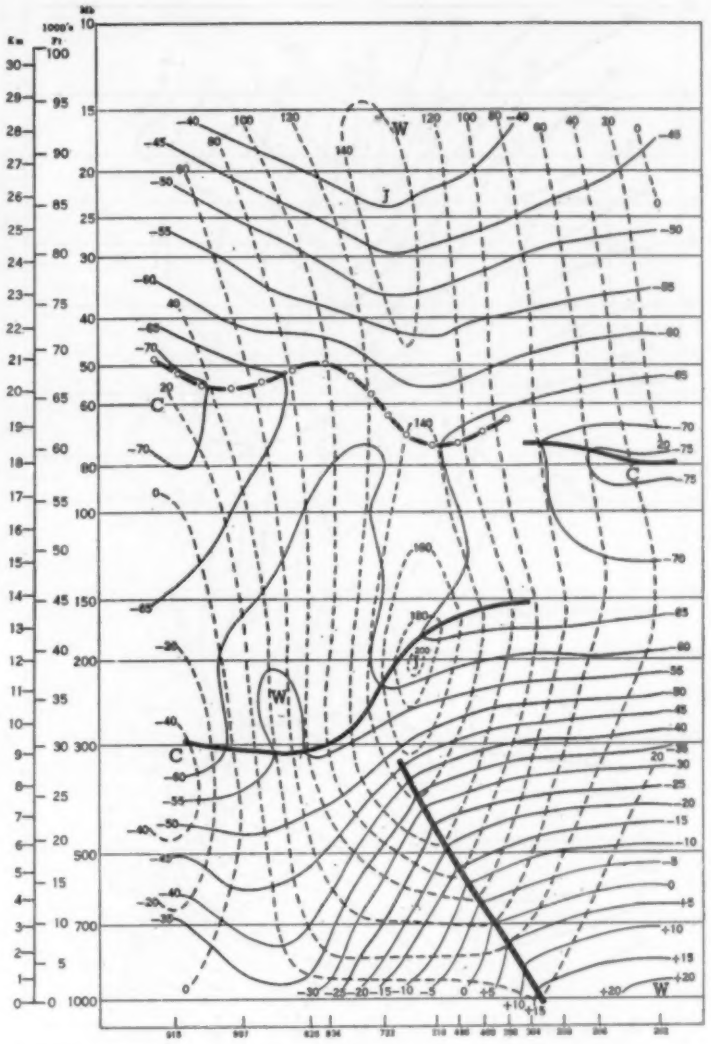

Figure 10.—Cross section for January 27, 1957, from Miami, Fla. (202) to Coral Harbour, N. W. T. (915) as delineated in figure 8. Analysis includes front (very heavy line), tropopause (heavy line), stratopause (heavy line with circles), isotherms (thin lines), and isotachs (dashed lines). Core of westerly jet stream shown by letter J.

not only increased downstream but also was increasing with time as the isentropic surfaces become farther depressed. The kinetic energy apparently was being converted into potential energy as represented by the increased tilt of the isentropic surfaces surrounding the warm center. The isotach-isotherm pattern changed with height so that at the 25-mb. and 15-mb. surfaces the center of strongest winds was very close to the warm center, a relationship to be expected if the warm center and thus the strong temperature gradient northward from the center were produced by forced sinking into a lower layer of divergence. The vertical slope of the warm center into the upstream direction and toward the low pressure side of the current also agreed with the concept of a current flowing to the right across contours to produce convergence with sinking in lower layers to the right of the stream and divergence with sinking in higher layers to the left of the stream.

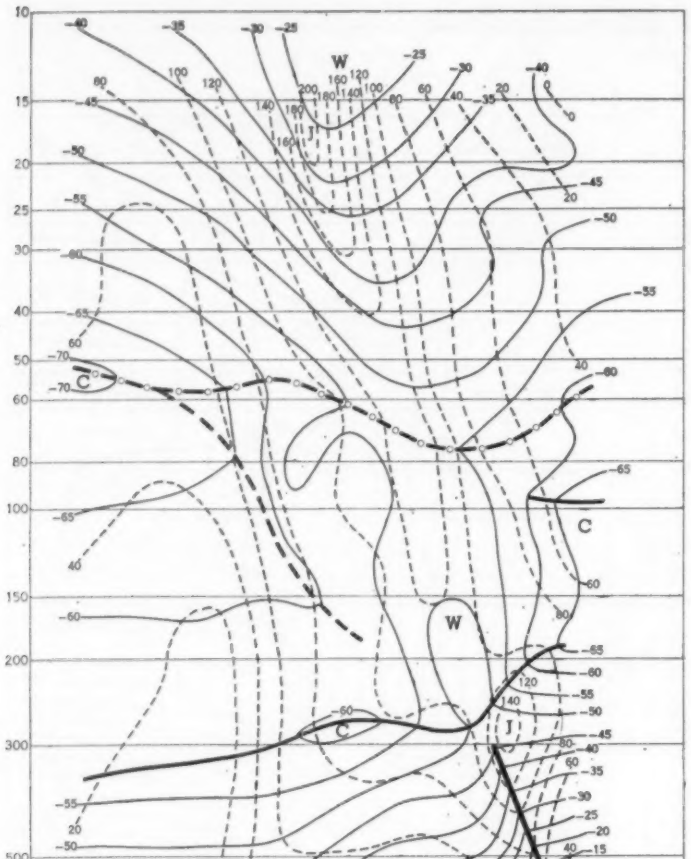

Figure 11.—Cross section for January 27, 1957, from Atlantic Ship E to Churchill, Manitoba (913) as delineated in figure 8. Analysis as in figure 10 but with lapse rate discontinuity shown by heavy dashed line.

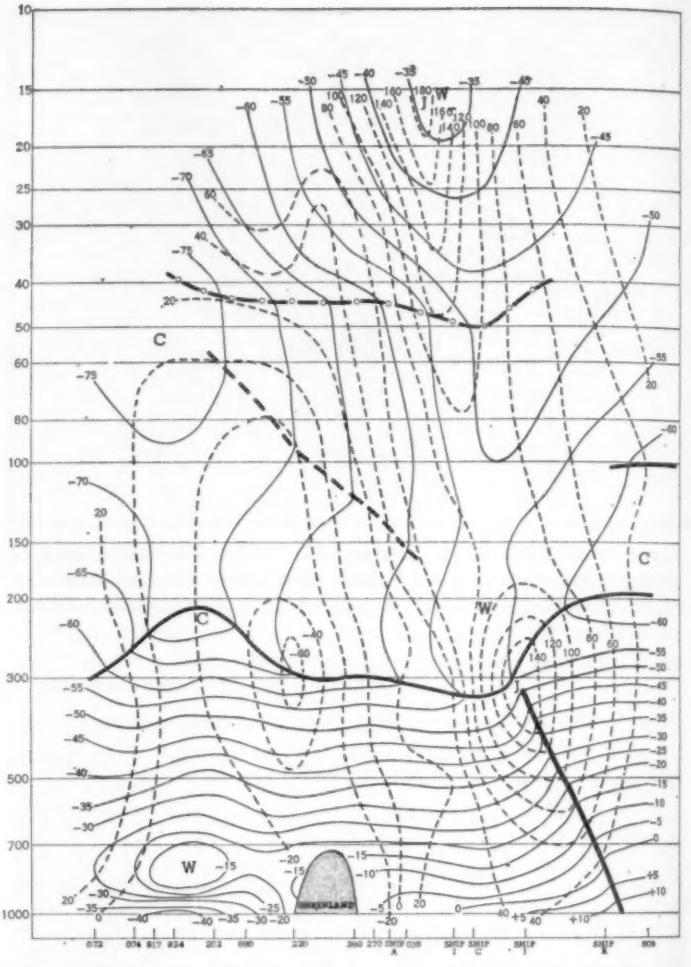

Figure 12.—Cross section for January 27, 1957, from Lajes, Azores (509) to Mould Bay, N. W. T. (072) as delineated in figure 8. Analysis as in figure 11.

To illustrate the interrelationship of wind flow and temperature field in greater detail, three cross sections (figs. 10, 11, and 12) were constructed nearly perpendicular to the wind flow at the higher levels and along lines shown in figure 8. Vertical slopes of all features are greatly exaggerated by the large distortion of the vertical scale, about 200 to 1. Godson and Lee [6] used similar cross sections in their description of this and earlier cases and also in their description (Lee and Godson [10]) of the Arctic stratospheric jet stream over Canada during the winter of 1955–1956. The cross sections shown here include the more prominent tropopauses, to aid in distinguishing tropospheric airmasses from those of the stratosphere.

At least four stratospheric airmasses can be identified although their boundaries, drawn at the cold side of the transition zone, were sometimes indistinct. Above the tropical tropopause, usually found in or near the 80- to 100-mb. layer, there was the *tropical stratospheric airmass with moderate temperature inversion*. Above and north of the tropospheric jet stream was the *warm isothermal stratospheric airmass of the high mid-latitudes*. To the south of this airmass between 100 and 200 mb., temperature decreased toward the high cold tropical troposphere, and to the north temperature decreased toward the *Arctic stratospheric airmass* that forms in the darkness of the polar night. There is generally a slight lapse rate in the latter airmass, but soundings taken on its periphery sometimes show an upper boundary above which there is an isothermal lapse rate or inversion. In cases of anomalous warming, sinking motion in the upper stratosphere produces a *superior stratospheric airmass*, characterized by an inversion of 3° C. per km. or more and separated from the lower layers by the lapse rate discontinuity we refer to as the stratopause.

The geometrical relationship of the various features across a wide span of longitude is illustrated in figures 10, 11, and 12. These relationships may not be typical of all anomalous warmings since, as Godson and Lee [6] have demonstrated, there were remarkable dissimilarities among anomalous warmings that have been studied. Near 80° W.

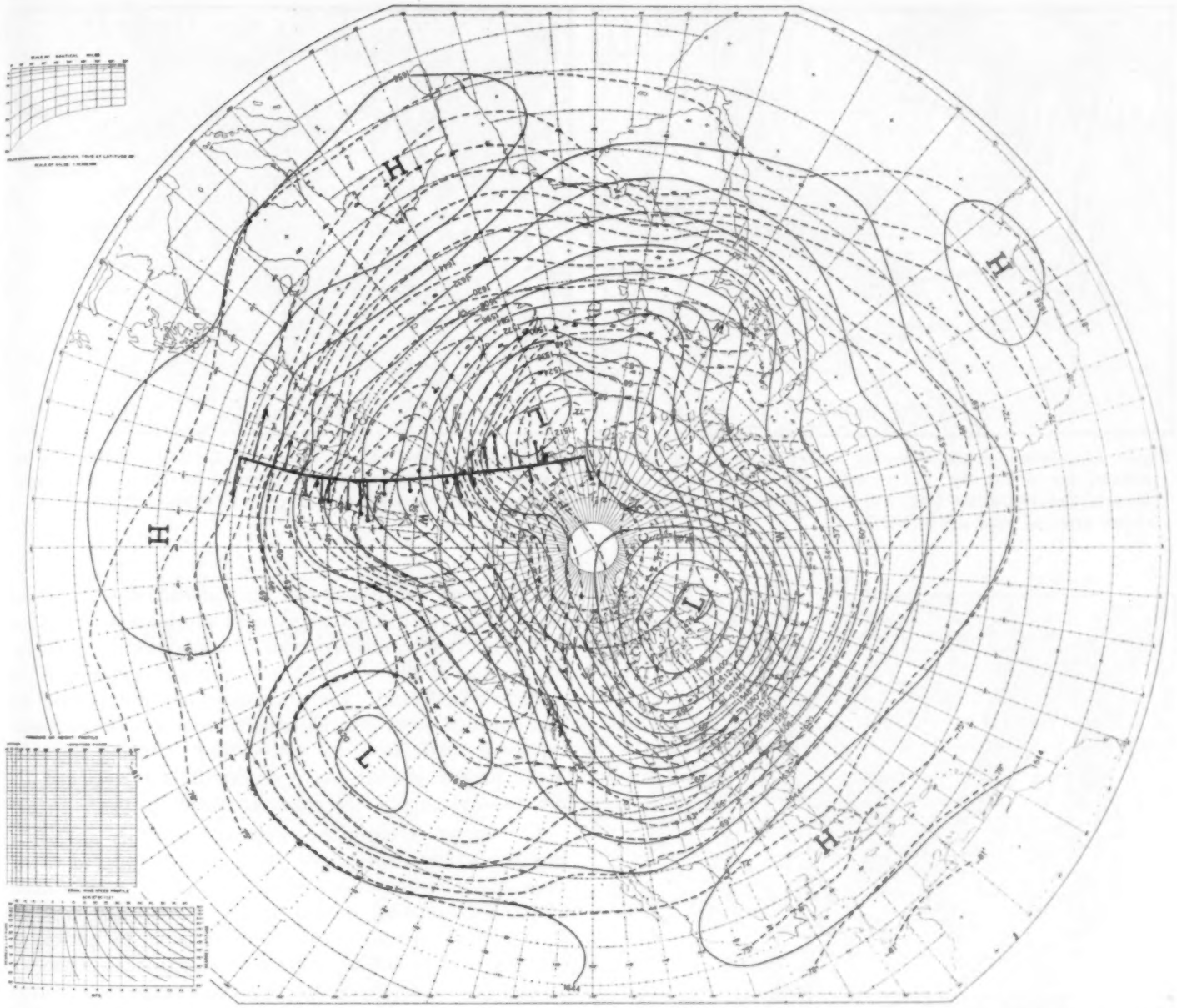

Figure 13.—100-mb. chart, February 1, 1957. Contours (tens of meters) are shown by solid lines, isotherms (°C.) by dashed lines. Line of cross section in figure 21 is shown by heavy line with dots locating nearby radiosonde stations.

(fig. 10) the jet stream of the polar front was exceptionally strong with speeds exceeding 200 kt. near 200 mb. The usual large decrease of speed above the jet core was greatly reduced here since the mid-latitude warm belt was pinched off by intrusion of the Arctic stratospheric airmass. Thus high wind speeds extended high into the stratosphere. The temperature gradient northward from the region of warmest stratospheric air and the associated vertical increase of westerly wind component were thus superimposed upon the belt of strong westerly winds and accounted for the upper stratospheric jet stream that appears near the top of the cross sections. In the cross section taken nearly through the center of warmest stratospheric air (fig. 11), the polar front jet stream was much weaker than farther west (fig. 10), but the stratospheric jet stream attained maximum strength in agreement with the strong temperature gradient northward from the center of maximum temperature.

The area of highest 100-mb. temperature in the easternmost cross section (fig. 12) was not surmounted by a strong inversion in the upper stratosphere, and the past movement of this 100-mb. warm center had been closely associated with the eastward-penetrating polar front jet stream. In this cross section, maximum temperatures at surfaces above 50 mb. were not as high as they were farther west (fig. 11) and all warming would be adequately explained by advection. Figure 12 extends far into the Arctic to show the structure of the stratosphere in the region of minimum temperature where because of the very low temperatures, radiosondes did not penetrate to the

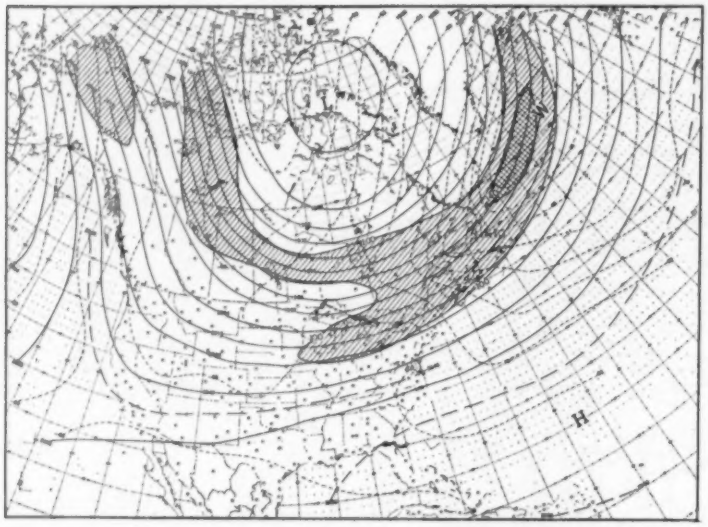

Figure 14.—50-mb. chart, February 1, 1957. Contours (tens of meters) are shown by heavy solid lines with intermediate lines dashed; isotherms (°C.) are thin dashed lines. Hatching shows areas of wind above 100 kt.

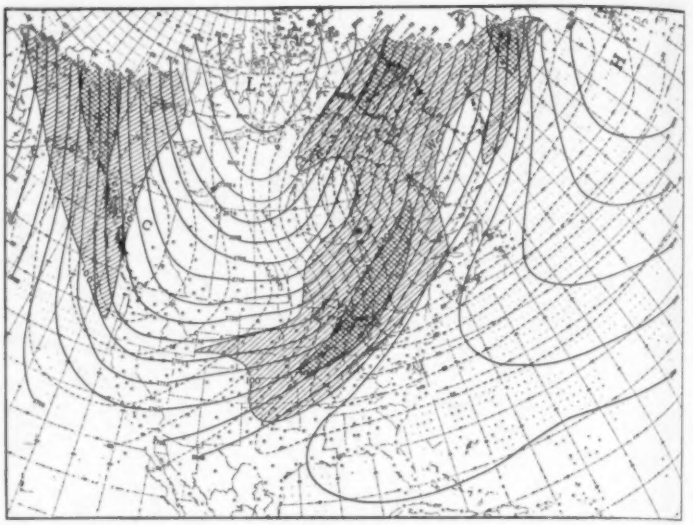

Figure 16.—15-mb. chart, February 1, 1957. Solid lines are contours, dashed lines mean isotherms for 25- to 15-mb. layer. Hatching shows areas of winds over 100 kt.

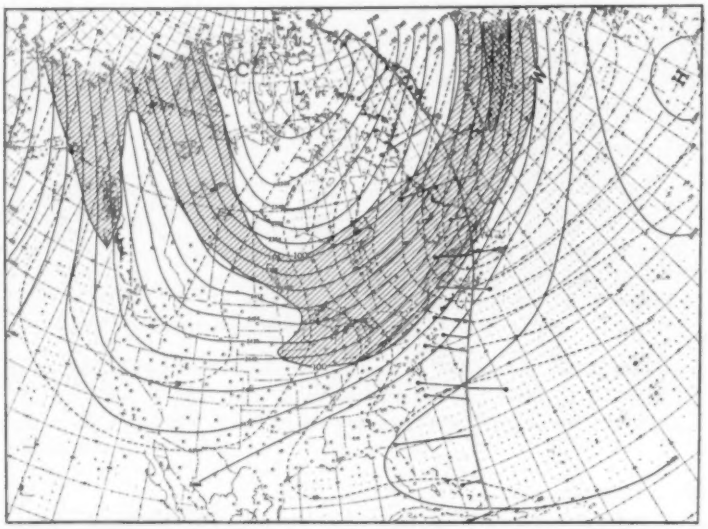

Figure 15.—25-mb. chart, February 1, 1957. Contours (tens of meters) are shown by solid lines. Isotherms (dashed lines) are means for the 50- to 25-mb. layer. Line of cross section in figure 19 is shown with dots locating nearby radiosonde stations.

greatest heights. The elevation of the Arctic tropopause to near the 200-mb. surface is an interesting feature of this cross section and confirms the observation, made by Riehl [15], of an exceptionally high Arctic tropopause in the vicinity of a cold stratospheric Low. A similar feature in the Antarctic was described by Schumacher [18].

5. THE MIGRATORY STAGE

Five days later, on February 1, the rate of intensification of the upper stratospheric warm center had diminished, but its northward movement had accelerated. Lower down in mid-stratosphere at 100 mb. (fig. 13), the Atlantic warm center had moved slowly toward the northeast between Greenland and the British Isles. Near the North Pole, continued increase of meridional circulation had permitted modification of the temperature with disappearance of the −75° C. isotherm and splitting of the −72° C. isotherm. The 100-mb. warm center over the east coast of Siberia had intensified and moved northwestward perpendicularly to the current. During the same 5-day period, marked retrogression at sea level and 500 mb. took place over the entire northern Pacific.

The upper stratospheric constant pressure charts for the North American sector (figs. 14, 15, and 16) clearly show the intensification and northwestward displacement of the warm center with height. The stratospheric jet stream was in nearly the same relation to the warm center as 5 days earlier except at the highest layer between 15 and 25 mb. where the warm air had progressively overspread the jet stream of the layers below to cause its decay with height as shown by the relatively disorganized 15-mb. isotach pattern. Over the Alaskan area on the western side of the trough, wind speeds increased with height up to the 15-mb. surface. However, soundings to above the 10-mb. surface at Salem, Oreg., and Spokane, Wash., showed a marked inversion above 15 mb. Radiosonde observations at western Alaskan stations to the right of the current did not extend above 15 mb. but showed only continued cooling with height to the top of the soundings. If there was no similar inversion to the right of the current, then the temperature gradient and vertical wind shear had become reversed above 15 mb., and the upper stratospheric jet stream in the area had reached its maximum at the 15-mb. surface.

The synoptic pattern in the upper stratosphere during this 5-day period changed very little over the North American continent, and even over the Atlantic there was little change up to the 50-mb. surface, but the rapid temperature rise above that surface in mid-latitudes was

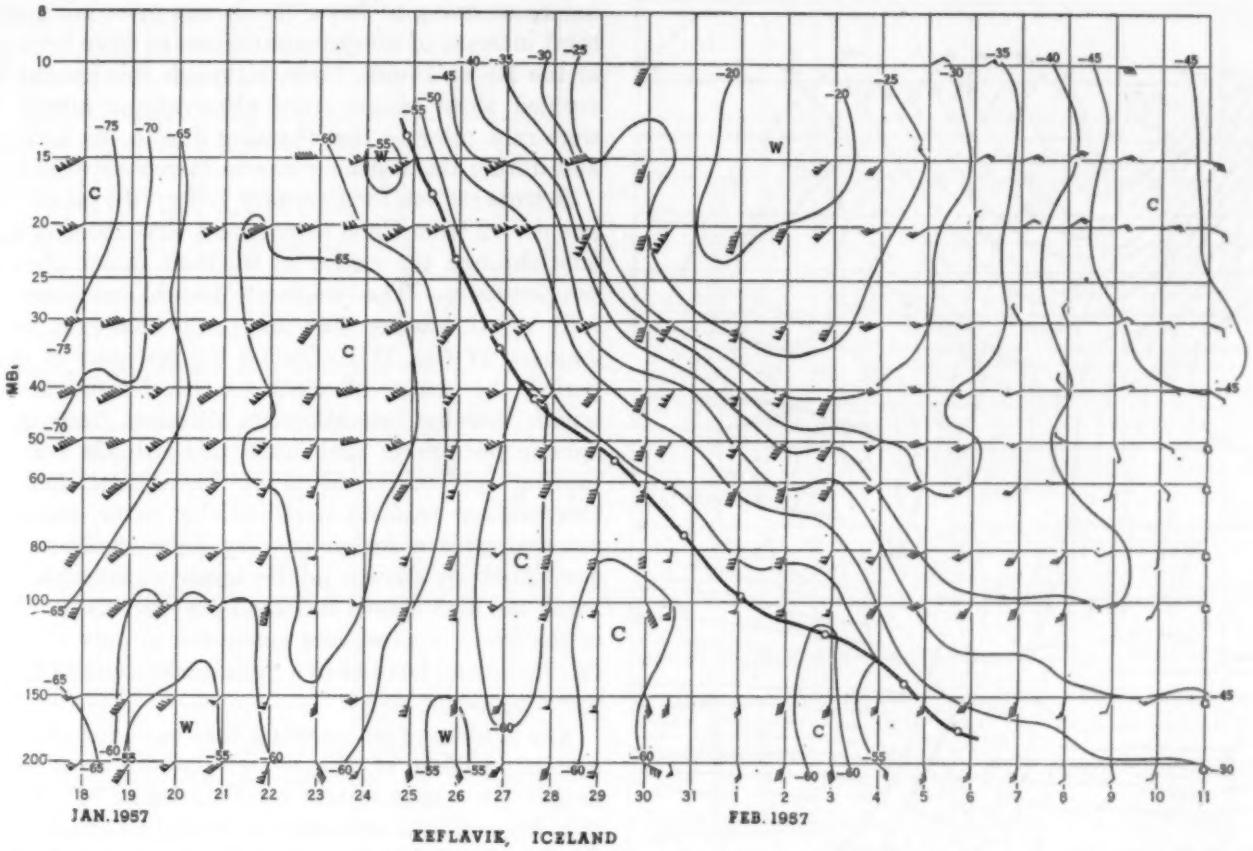

Figure 17.—Time section, January 18 to February 11, 1957, for Keflavík, Iceland. Isotherms are in °C., winds oriented from top of diagram for north. Heavy line shows stratopause. Vertical grid lines are for 1500 GMT of dates shown.

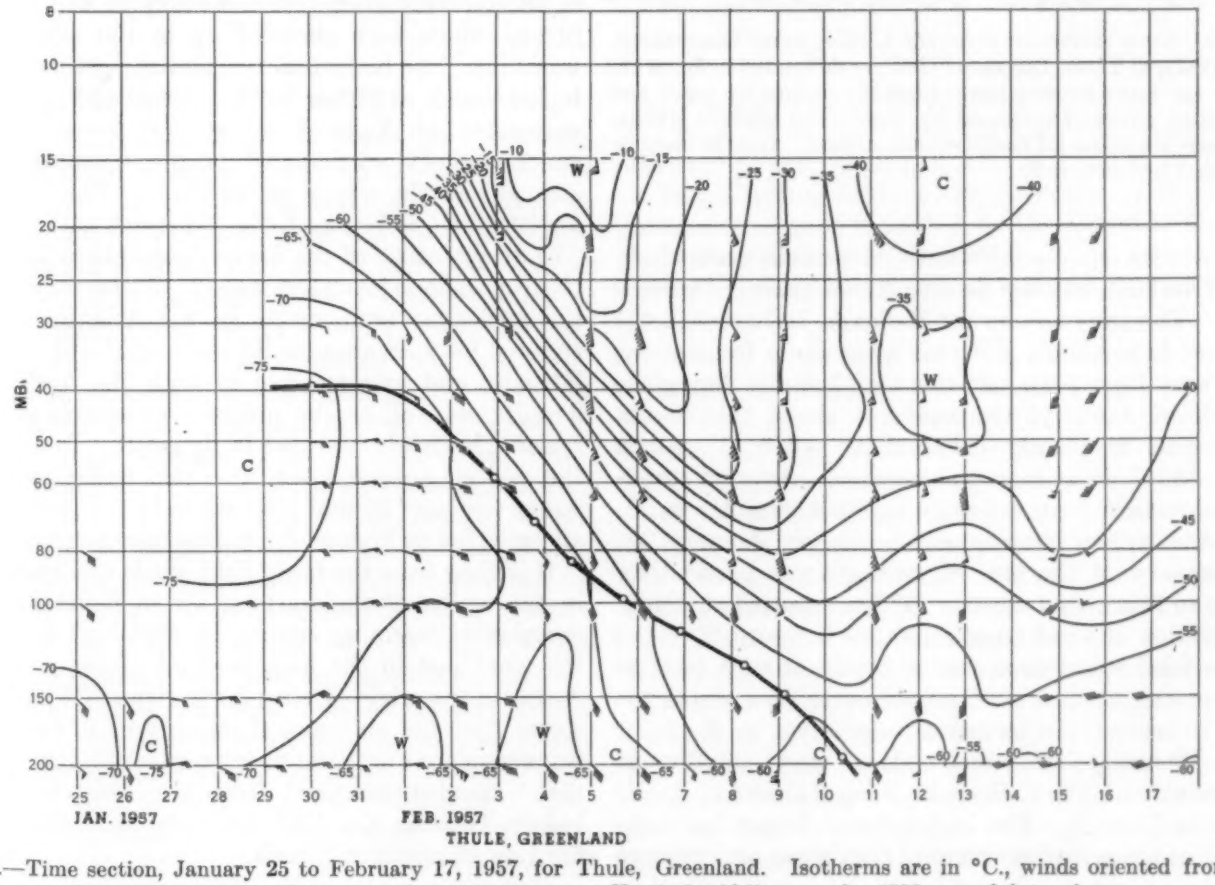

Figure 18.—Time section, January 25 to February 17, 1957, for Thule, Greenland. Isotherms are in °C., winds oriented from top of diagram for north. Heavy line shows stratopause. Vertical grid lines are for 1500 GMT of dates shown.

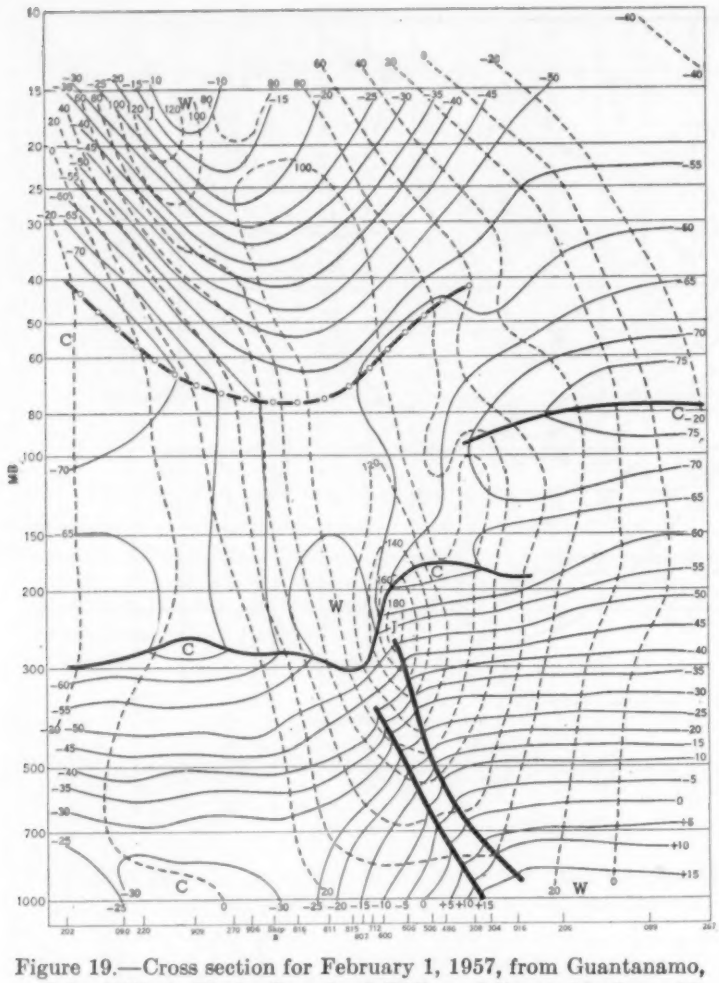

Figure 19.—Cross section for February 1, 1957, from Guantanamo, Cuba (267), to Thule, Greenland (202), as delineated in figure 15. Fronts are shown by very heavy lines, stratopause by heavy line with open circles, tropopause by heavy line without circles. Isotherms are thin solid lines, isotachs, dashed. Core of westerly jet stream is shown by J.

associated with equally rapid anticyclogenesis, particularly south of Iceland, as may be seen by comparing figures 9 and 16. The time section for Keflavik, Iceland (fig. 17) at 64° N. is markedly different from those for stations farther west (figs. 1–4). At this high latitude during the first half of January, temperatures above the 50-mb. surface were frequently lower than −75° C., falling below −80° C. in at least one instance. As wind speeds increased to more than 150 kt., a slow but irregular warming of the upper stratosphere began on January 18. After January 26 the rate of warming was particularly rapid up to February 1 when −15° was reported at 20 mb. An inspection of wind reports plotted in figure 17 shows that the wind speed decreased abruptly at each level as the warm axis at that level passed northward across the station to reverse the temperature gradient in the layer below. Warming also took place very rapidly at Narsarssuak and Thule, Greenland (fig. 18) and at Arctic stations in Canada. The higher levels began to warm first and at some stations reached maximum temperature before warming at lower levels was even initiated. The total increase of temperature seems to have been greatest in the 10- to 15-mb. layer, although this cannot be fully verified since temperature observations above 15 mb. were rare prior to the warming due to the extreme cold and during the warming due to increased wind speeds.

A cross section for February 1 (fig. 19), taken along the line drawn from Cuba to northern Greenland in figure 15, cuts through the center of warmest upper stratospheric temperatures. The warmest 15-mb. temperature was fully 15° C. warmer than that in the analogous section for January 27 (fig. 11). During the last part of the 5-day period the center of warm air accelerated toward the north, thereby increasing its distance from the tropospheric jet stream and other mid-latitude features and moving over colder air in the lower stratosphere. The temperature gradient north of the warm center became situated over a region of very light winds so that the associated jet stream in the upper stratosphere did not reach the high speeds found on previous days. Warming of the lower stratosphere amounted to only 2° or so in a day and could have been a radiational effect of the rapidly warming upper layers.

The simultaneous warming that occurred in the southeastern portion of the trough located over Siberia is detailed in a time section for Yakutsk at 74° N., 130° E. (fig. 20) and in a cross section from Iwo Jima to Novaya Zemlya (fig. 21), taken along the line shown in figure 13. At 80 mb. above Yakutsk, a total temperature increase of 30° C. occurred between January 24 and February 5. Strong winds were observed up to 100 mb. during the warming. The horizontal temperature gradient indicated higher speeds at higher levels. A stratopause was hardly detectable at Yakutsk where the lower stratosphere simultaneously participated in the warming almost as strongly as the upper stratosphere. The cross section for 0200 GMT, February 1 (fig. 21) agrees with this feature. The temperature of the lower stratosphere just north of the tropospheric jet stream was 10° C. or more warmer than the analogous temperature in the Atlantic area. The contrast between abnormally warm stratosphere in middle latitudes and extreme cold in both the Arctic and the Tropics, as well as the different structures of the cold regions, is clearly revealed in figure 21. In the Tropics, the cold air appeared only as a thin wedge at the tropopause (see also [9] and [13]) while in the Arctic the cold air extended as high as the radiosondes penetrated.

It is clear from the fairly light winds and variable shear in the region of the warmest air in figure 21 that the exceptional warming cannot be explained by action of the wind just in the neighborhood of the cross section. A clue to the origin of warming is given in figure 13 which shows that the air warmed steadily as it decelerated in traversing the quasi-stationary region of isobaric difluence that extended eastward from the constriction of the isobars between the High over the Bay of Bengal and the Low in northern Siberia.

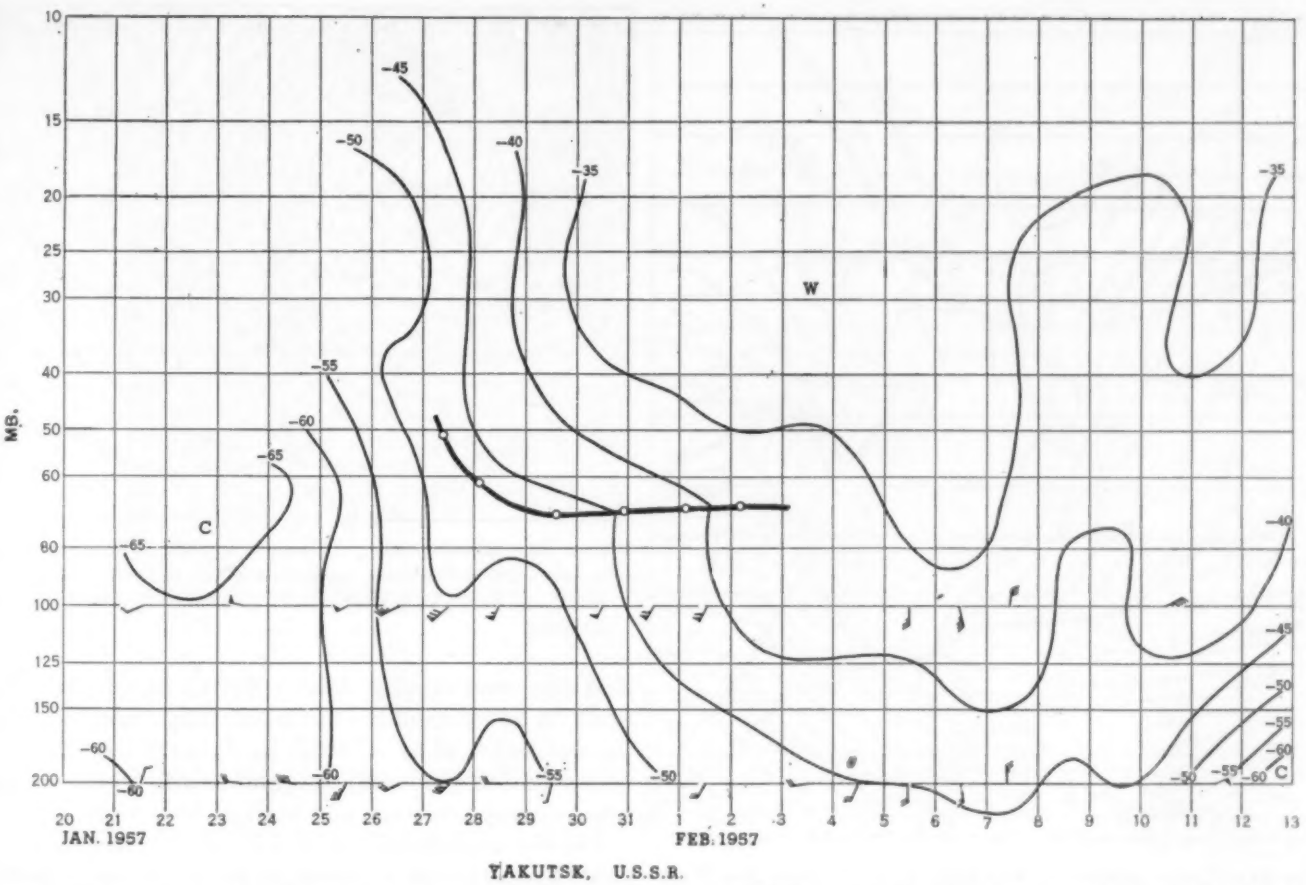

Figure 20.—Time section, January 21 to February 12, 1957, for Yakutsk, U.S.S.R. Isotherms are in °C.; winds oriented from top of diagram for north. Heavy line is stratopause. Vertical grid lines are 1500 GMT on dates shown.

6. THE MATURE STAGE

A glimpse of the warm area over North America during the mature stage is afforded by the 25-mb. chart for February 6 (fig. 22). Around the low center then moving southwestward across Canada, there was a nearly uniform vortex of winds of about 100 kt., in contrast to the jet stream with marked maximum speed that appeared on January 27 (fig. 8) and February 1 (fig. 15). The cold air off the west coast of the continent was completely pinched off from its Arctic source region, but the minimum temperature at 25 mb. remained almost unchanged in spite of the large increase of temperature in the other quadrants of the Low. Continued anticyclogenesis over the Atlantic culminated in a closed High, moving toward the northwest. The magnitudes of the height rises at various levels as the High passed over Iceland can be compared by means of a graph of the heights of constant pressure surfaces at Keflavik (fig. 23). During the first half of January there was close correspondence between height changes of all constant pressure surfaces with a slight vertical increase of amplitude to indicate slight warming accompanying the height rises. After January 23 the 15-mb. surface began to rise and with it the 30-mb. surface, but at a slower rate. The 100-mb. surface rose briefly but then settled back again until February 2 when a strong, steady rise began. The amplitude of rises was much greater at the upper levels, amounting to 2,500 m., or 8,000 ft., at 15 mb. in the two weeks following January 23 and ranging over a full 3,300 m. or 10,800 ft. at 10 mb. during January and February. The percentage pressure change is indicated by the fact that the 15-mb. surface at Keflavik on several days in early February was at a greater height than the 10-mb. surface had been on January 5.

A view of the vertical temperature distribution on February 6 through the Atlantic High and Canadian Low is afforded by a cross section (fig. 24), taken along a curved line (fig. 22) from the Azores to Oregon. The −5° C. isotherm concurs with the observation of −3.4° C. at 11 mb. at Churchill 12 hours earlier. This observation, listed in the Northern Hemisphere Data Tabulations [25] was discussed by Lowenthal [11] who also mentioned an unlisted report of −3.5° C. at 7 mb. on February 6 at Salem. This latter report would indicate that the warming effect at very high levels had spread almost completely over the coldest air in mid-stratosphere and that the −5° C. isotherm should be open at the top. The maintenance of low temperature near 50 mb. in the same atmospheric column with far warmer air below and above is remarkable and requires an explanation through dynamic process since the isotherms everywhere moved much more slowly than the winds. Over the Atlantic stratospheric warming

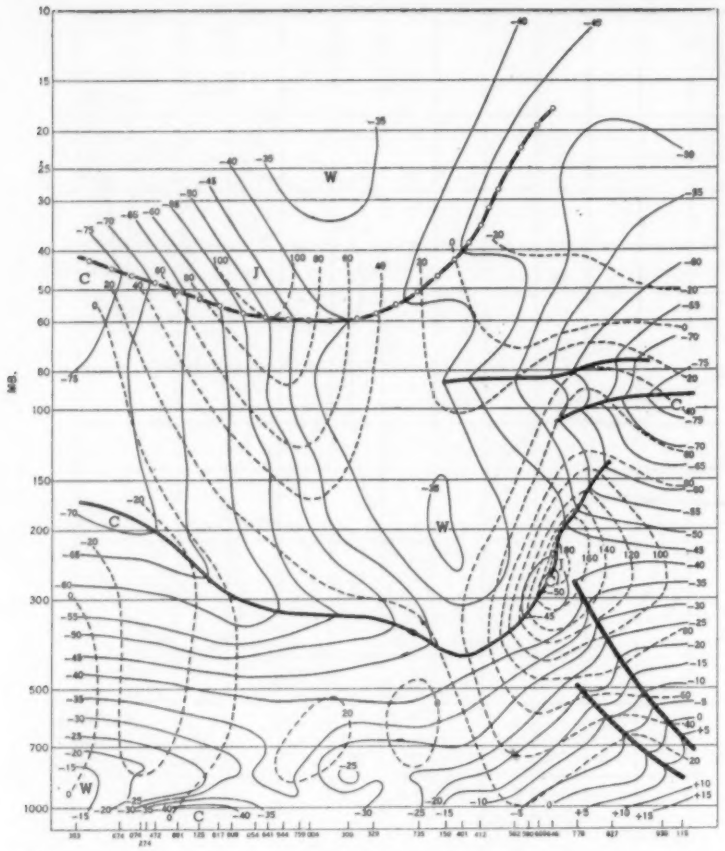

Figure 21.—Cross section for February 1, 1957, from Iwo Jima (115) to Cape Zhelaniya, Novaya Zemlya (353) as delineated in figure 13. Fronts are shown by very heavy lines, stratopause by heavy line with open circles, tropopause by heavy line without circles. Isotherms are solid lines, isotachs dashed. J shows center of westerly jet core.

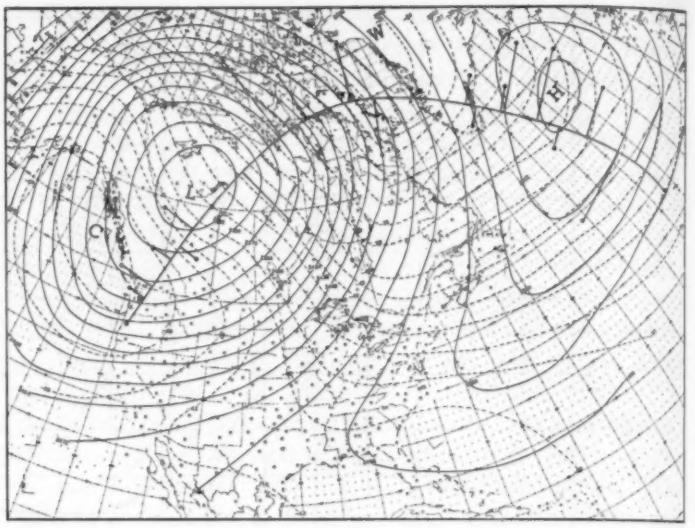

Figure 22.—25-mb. chart, February 6, 1957. Contours (tens of meters) are solid lines, isotherms (°C.) dashed. Line of cross section in figure 24 is shown with dots locating nearby radiosonde stations.

penetrated downward until the stratopause merged with the tropopause. Southward from the sloping axis of warmest air in the stratosphere, a nearly isothermal condition was achieved as temperatures returned to more seasonable values.

To illustrate other aspects of the warming phenomenon, the tracks of the warm and cold centers at 25 mb. are shown in figure 25 (adapted from Thompson [21]). On January 16, a warm center became definable on the United States-Canadian border and moved eastward for four days in a direction nearly that of the wind blowing through it but at a much slower speed. During this early stage, the 25-mb. warm center, displaying vertical linkage through an exceptionally deep layer (see also figs. 1–4), moved along directly above a very cold, intense trough in mid-troposphere. This is illustrated by the time section for Stephenville (fig. 4) where on January 19 and 20 the passage of the warm stratospheric air was accompanied by a low tropopause surmounting the very cold tropospheric air. During the diffuse stage from January 20 to January 25, the warm mass of air at 25 mb. spread amorphously over a portion of the eastern Atlantic, and the position of the center was uncertain. On January 22, the center came to a halt and began to retrogress against the wind flow. Its central temperature rose slowly at first but more rapidly, from −41° C. to −32° C., during the first 24 hours of the intensification stage beginning on January 25, and to −18° C. by January 29. Movement of the center was nearly perpendicularly to the left of the wind during this stage and until at least February 10.

On the western side of the continent, the cold center, with temperatures as much as 68° C. lower than in the warm center, could be definitely located only on the four days from February 1 to 4. It also moved nearly perpendicularly to the wind but to the right. Examination of the 25-mb. charts at 24-hour intervals reveals an interesting parallelism of trajectories of cold center, cyclone center, warm center, and anticyclone center, one following almost in the tracks of the other with warm center and anticyclone developing as cold center faded and cyclone center filled.

7. INTERPRETATION AND CONCLUSIONS

At this time it is logical for the reader to ask how the 1957 warming epoch differed from the usual behavior of the stratospheric circulation and whether the circulation and its variations can be explained in the same way as their tropospheric counterparts. It would be unwise to draw general conclusions solely from the circumstances attending a single exceptional case. Yet a case having features of heroic proportions is most likely to suggest profitable avenues of investigation, and the search in this instance is facilitated by several types of source material already in the literature. From published mean values [9, 14, 22] anomalies can be approximated. Several case studies of the circulation patterns accompanying the annual departure of the Arctic stratospheric airmass from the polar region are available for comparison [2, 16, 19, 20, 28]. Numerous mathematical formulae for the amplification of perturbations have been derived, e. g. [4, 5], and may be evaluated for their applicability to observed conditions. However, since this paper is essentially descriptive, only a brief explanation is given here and a

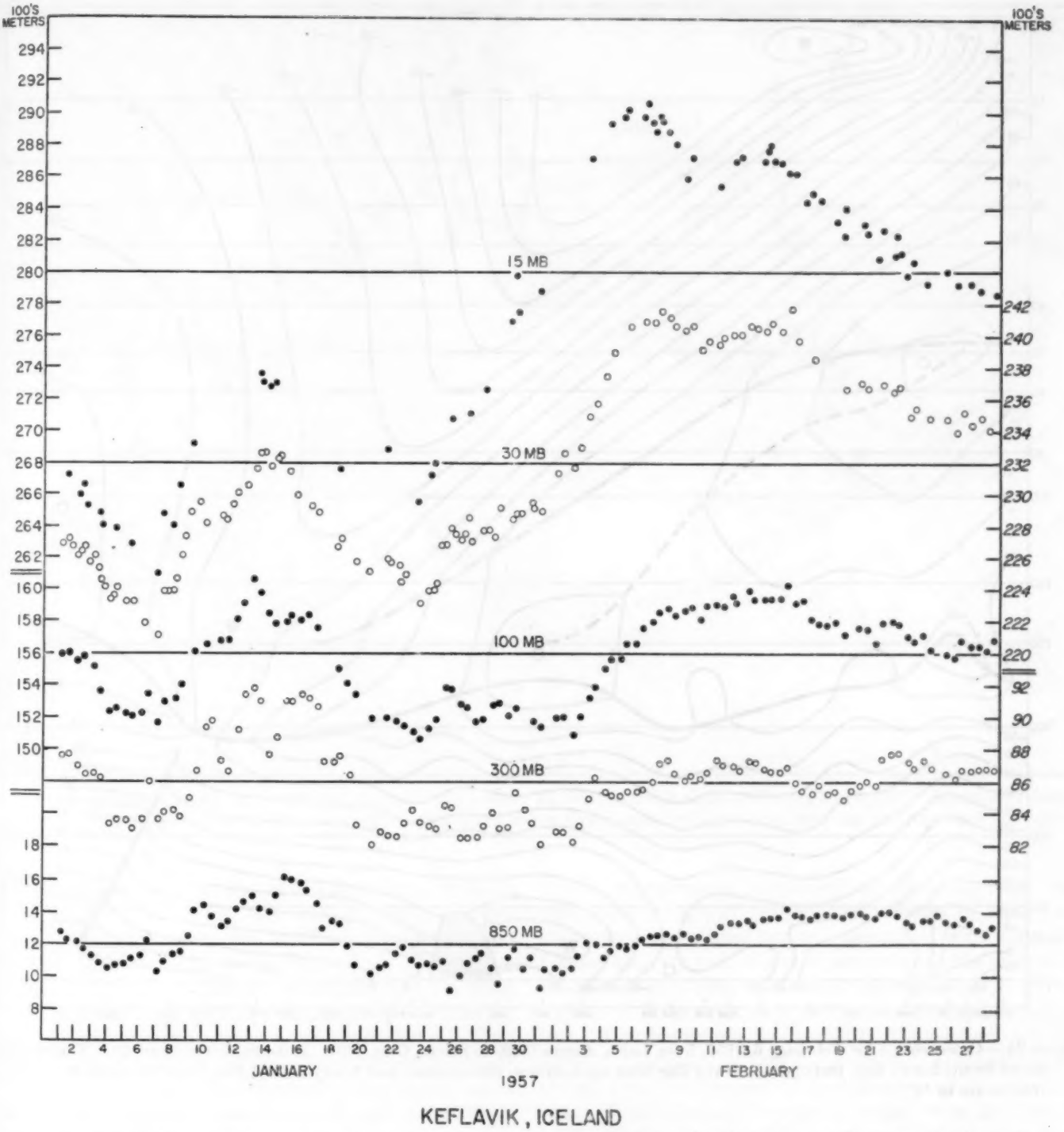

Figure 23.—Height of 850-mb., 300-mb., 100-mb., 30-mb., and 15-mb. surfaces at Keflavik, Iceland, during January and February 1957. Scales for open circle points are on right. Along the abscissa, lines show 0000 GMT for each date.

more complete discussion reserved for a later paper. As one means of limiting the length of this paper interrelationships, similarities, and differences between stratospheric and tropospheric circulations have been discussed only briefly here. A great amount of work needs to be done on the subject, and the attention of research meteorologists is cordially invited.

The Arctic area that is deprived of radiation during polar darkness is perfectly circular and thus we would expect to find a peripheral, horizontal temperature gradient along the circumference. The accompanying vertical wind shear and high level jet stream should be zonal. But the observed jet stream tends to exhibit anticyclonic flow over the Aleutian-Alaskan area and cyclonic flow over eastern Canada and Greenland. From available data, it is assumed that so marked a forced perturbation does not exist in the Antarctic. Thus we have the interesting phenomenon of a topographic feature influencing the circulation of the high stratosphere. Differential radiation from the warm Aleutian ocean area versus that

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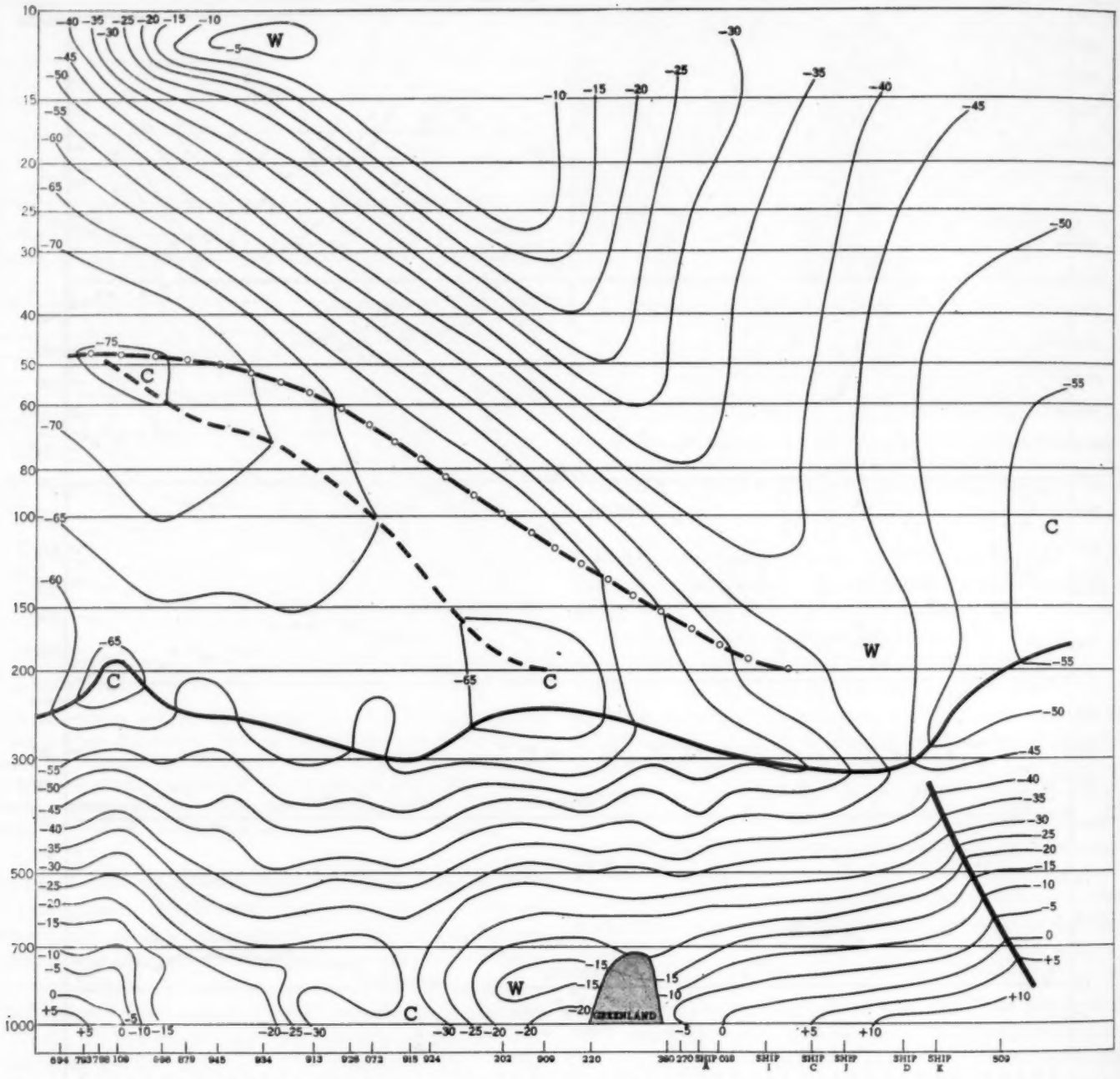

Figure 24.—Cross section for February 6, 1957, from Lajes, Azores (509) to Salem, Oreg. (694), as delineated in figure 22. Very heavy line shows front; heavy line, tropopause; heavy line with open circles, stratopause; and heavy dashed line, lapse rate discontinuity. Isotherms are in °C.

from the cold Greenland ice cap is in the right sense to explain the warmer stratosphere over the Aleutians and thus the presence there of a warm high-level ridge in contrast to the cold stratospheric trough that seems to be normal over western Greenland during the first months of darkness. This same reasoning was used by Schumacher [17] to explain the fact that in the Antarctic, where the surface is colder than in the Arctic, the stratosphere exhibits temperatures 5° or 10° C. colder than have been measured in the Arctic stratosphere. However, the following explanation is given in terms of the vertical and horizontal circulation which may be a contributing, or even the entire, cause of the forced perturbation.

In the high troposphere over Japan flows the most powerful sector of the jet stream, with its position and steadiness determined largely by the horizontal temperature gradient maintained across the Himalaya Mountains [32]. After passing beyond Japan this jet stream decelerates and in so doing forces an indirect circulation in the vertical cross section taken north-south across the central Pacific. In the Aleutian area, the indirect circulation requires rising motion below the level of the jet core and sinking motion above and in consequence forces the formation of a semipermanent cold Low in the troposphere and warm ridge in the stratosphere. On the eastern side of the ridge, the northwesterly flow taps the

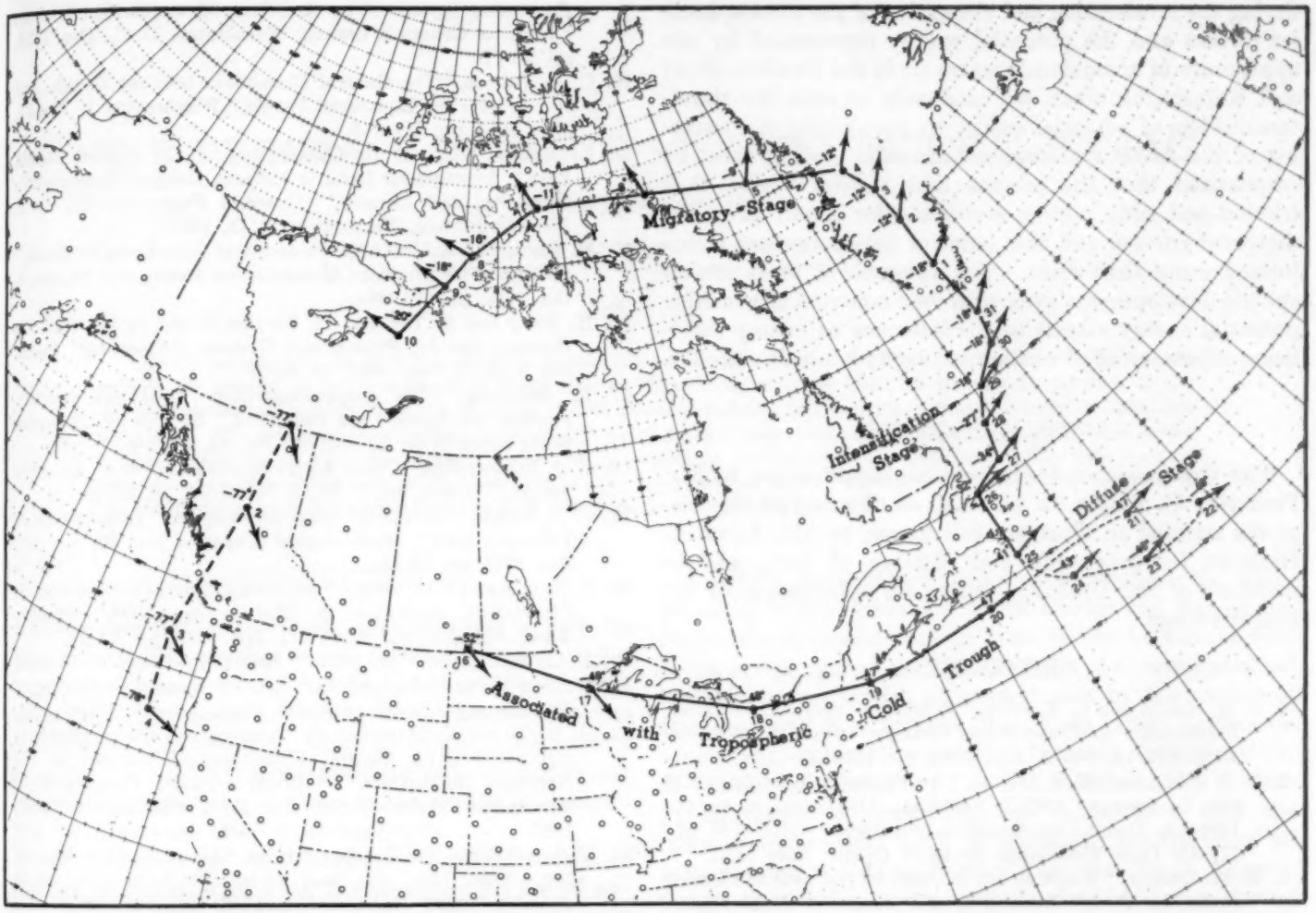

Figure 25.—Trajectory of 25-mb. warm center, January 16 to February 10, 1957, and cold center, February 1 to 4, 1957. Location of centers each day at 1500 GMT is plotted with maximum temperature above, date below, and arrowhead pointing with the wind through the center.

cold air source at the pole, and as the flow, in accordance with the conservation of absolute vorticity, swings around cyclonically near the south of Greenland, the cold stratospheric trough is formed. This explanation seems more convincing than that based on radiation from the surface since warm air not continuously produced by dynamic means could too easily be advected away. That the warm ridge is at times certainly dynamically produced is shown by occasional intensification above cold sources during progression over Canada (1958) or retrogression over Siberia (1957).

Most mathematically derived formulae for amplification of perturbations show baroclinicity or vertical wind shear to be the most critical parameter under the conditions that exist in the upper stratosphere, and baroclinicity approaches the critical value there only on the periphery of the Arctic stratospheric airmass. The Aleutian ridge is a preferred locale for large baroclinicity because it is there that warm air is found nearest the pole. Thus in most years amplification of the Aleutian ridge and its eastward movement away from the area of its origin are important elements in the observed breakdown of the Arctic stratospheric jet stream.

The retrogressive movement of Aleutian ridge and Greenland trough in January 1957 seems to have been an unusual occurrence but was associated with unusually intense activity and so was in accord with the statement by Austin and Krawitz [1] that retrogression is characteristic of stratospheric perturbations during intensification. Possible influences exerted by tropospheric activity were a forced meshing with the anomalous quasi-stationary trough over the western United States and the blocking action of the column of warm air created over the Atlantic by the dissipation of the kinetic energy of the tropospheric jet stream.

The location of the intense 1957 warming on the eastern side of the trough was apparently exceptional but may seem so only because in previous years the eastern portion of the trough was much farther east and so beyond the region of adequate observations. Alternatively, it may eventually be shown that great warming of the eastward portion of the trough is a characteristic of retrogression. In any case, it seems that the exceptional intensity of the warming was at least partially a result of the exceptional strength of the preexisting tropospheric jet stream.

For the principal source of the kinetic energy created

during the acceleration and elongation of the stratospheric jet stream and the potential energy represented by the appearance of anomalously warm air in the Newfoundland and Kamchatka areas, we need only to note the simultaneous loss of potential energy by the sinking and warming of the Arctic stratospheric airmass. Still it must be emphasized that the process took several weeks, that friction and eddy motion accounted for a portion of the dispersed energy, and that some of the energy was transformed more than once. The slowness of most stratospheric developments even with vast amounts of available potential energy attests to the influence of strong stabilizing effects, chief of which must be hydrostatic stability.

ACKNOWLEDGMENTS

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THE BIRTHPLACE OF NORTH ATLANTIC TROPICAL STORMS

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[Manuscript received June 19, 1958; revised August 29, 1958]

ABSTRACT

Newly adjusted tracks of North Atlantic hurricanes and tropical storms for 72 years provide a consistent set of data for examining the birthplaces of these storms. For 59 years (1899–1957) of the record, portions of the adjusted storm tracks from the point of origin of first closed circulation to the point of first hurricane intensity are presented. The origins show a regular seasonal shift eastward and later westward across an area east of the Lesser Antilles. The location of the seasonal maximum of origins in this area is thus explained. The data support Mitchell's conclusion that the eastern Caribbean is not a birthplace of tropical storms. The results are discussed in relation to the available observational network in the hurricane breeding grounds.

1. INTRODUCTION

Forecasters frequently search climatological records for clues to probable weather events at the present or in the immediate future. The climatological records of tropical storm behavior are no exception to the search but one encounters difficulties if he does not examine the records carefully. Among the climatological aids suggested are some that relate storm motions to the season and origin. Yet the origins are often quite uncertain.

The birthplace of any particular tropical storm is difficult to locate with even a reasonable degree of accuracy. Riehl [9] pointed out that tropical storms form in pre-existing disturbances, waves, or shear lines, and that deepening may be a slow process requiring days, or it may be explosive.

The literature contains conflicting statements about the birthplaces of even such important storms as hurricane Connie of 1955 and the New England hurricane of September 1938. Namias and C. Dunn [7], in discussing the formation of hurricane Connie, stated: "While hurricane Connie was first reported on August 4 at about 16.6° N. and 48.0° W., there is some indication that it developed off North Africa some time earlier." Authors have variously put the birthplace of the September 1938 storm at longitudes 68° W., 50° W., 37° W., and 5° W. Hubert [5] traced a storm circulation, which developed into the devastating New England hurricane, from a point over West Africa at 5° W. on September 7, 1938. Brooks [1] discussed several versions of this track; figure 1 is from his paper. Pierce [8] stated: "The actual history of the storm goes back to some time before September 13th, when it was noticeable in the region of the Cape Verde Islands." Tannehill [10] said of this storm shortly after its occurrence: "There was some evidence of cyclonic circulation central about 19° N., 37° W., on the morning of September 13, 1938 . . . ." Later, Tannehill [11] commented: "There are some indications that this hurricane originated near the Cape Verde Islands . . . ."

Previous investigators have tried to establish the birthplaces of North Atlantic tropical storms and hurricanes. Mitchell's [6] classic work on West Indian hurricanes was, in his words, "prompted by the results of a more restricted investigation—namely, an examination by the author of the idea, long held by him, that West Indian hurricanes *never* originate over the eastern two-thirds, approximately, of the Caribbean Sea . . . . The results of this investigation proved so interesting and informative that the more comprehensive work of replotting the tracks of all tropical storms that originated over the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico during the entire period for which daily charts of the North Atlantic are available, 1887 to date [1924], was undertaken." Tannehill included a chapter on the "Origin of West Indian Hurricanes" in his text [11] and used the intersections of the tracks of storms from different areas as an indication of place of origin.

Dunn [2] in discussing areas of hurricane development stated: "Obviously this area is not a point, yet the concept is meaningless if it is expanded to encompass the entire known existence of the wave prior to the attainment of hurricane intensity." He did not attempt to define the "area of development," but for all storms from 1901 to 1955 located that point on each hurricane track where the storm first reached hurricane intensity.

2. ESTABLISHMENT OF TRACKS

In the present investigation the tracks of all North Atlantic hurricanes or tropical storms known to have occurred from 1886 through 1957 were examined in the Marine Section, Office of Climatology, U. S. Weather Bureau [13]. The extensive work done earlier by Mitchell [6], Tannehill [11], Fassig [4], and Tingley [12] was reviewed and all charts and articles in the several issues of the *Monthly Weather Review* for these years were studied. A set of revised annual track charts based on all these sources was prepared. As a result of reviews by person-

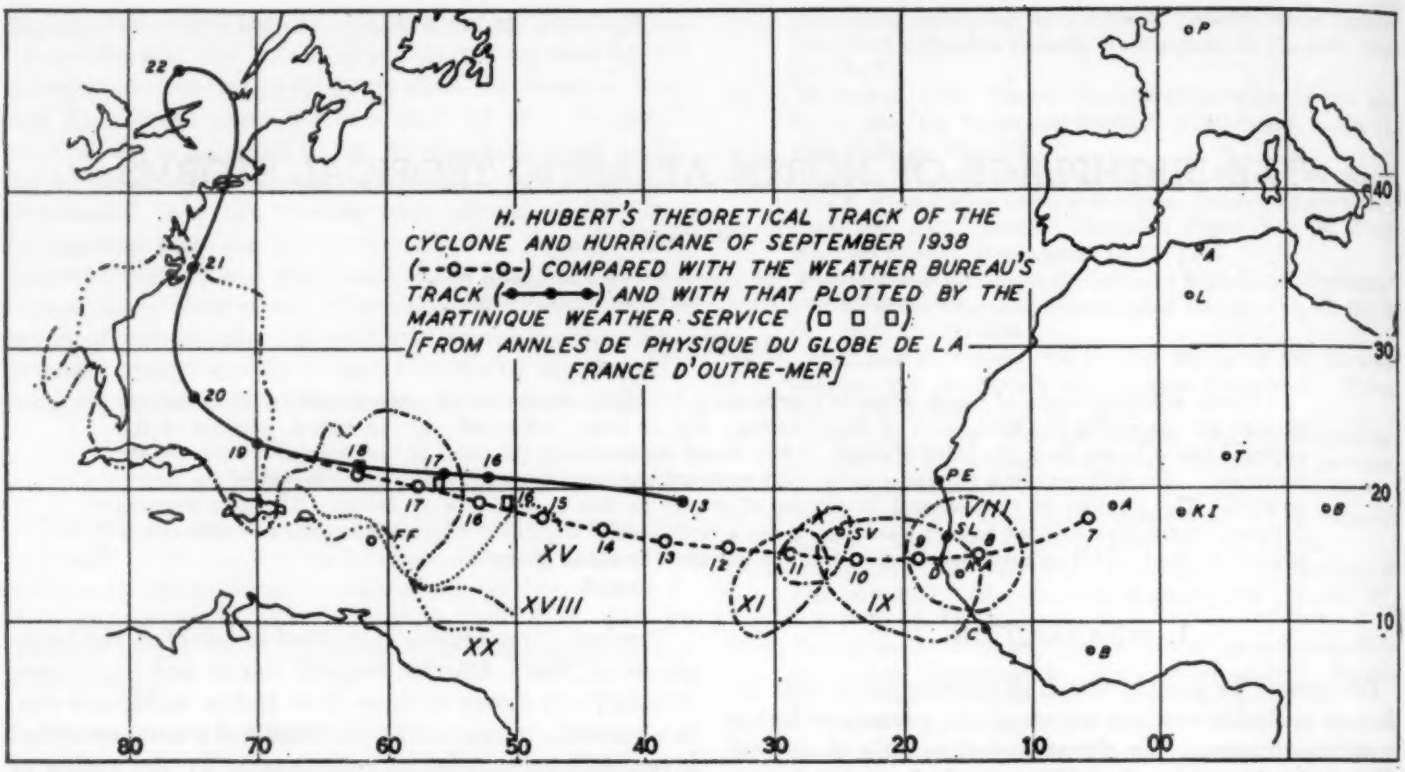


FIGURE 1.—Versions of the track of the New England Hurricane of September 1938. (After Brooks [1]). Positions of 1015-mb. isobar are shown by light broken lines and dates indicated by Roman numerals; Weather Bureau's version of track from September 20 to 22 was revised by Pierce [8] who placed track on 73d meridian from Cape Hatteras to southern Vermont.

nel of the Weather Bureau's Extended Forecast Section, Hydrometeorological Section, National Hurricane Research Project, and hurricane forecast offices in Miami, San Juan, and New Orleans, many adjustments of the tracks were made. Mutual adjustments between these charts and those developed by Dunn were necessary in the tracks and the points where hurricane intensity was first reached.

For the years 1899 through 1957, an effort was made to separate the tracks into portions according to the current intensity of the storm. The exact point in its track at which a storm attained tropical storm intensity is naturally somewhat questionable. The point of origin of the storm circulation, sometimes subjectively determined, represents a best estimate of the location of the first closed circulation that could be tracked to the area where later a storm of tropical storm or hurricane intensity is believed to have been. The individual tracks may not provide a true representation of what occurred in Nature, but they were drawn with a consistent set of considerations throughout the period.

3. REGIONS OF ORIGIN

A schematic portrayal of track origin areas, or regions of development, was included in an article compiled by Office of Climatology of the U. S. Weather Bureau [14]. Examination of the monthly charts of the frequency of track origins by 2½° areas, published in that article, shows the well known seasonal shift in the main area of origin from the western Caribbean and Yucatan in June eastward to the Bahamas and even to Cape Verde in mid-season and then gradually back to the western Caribbean by November. Although in that article the breakdown is by months, it is consistent with the information published by Dunn [3] regarding region of origin and season.

The large maximum of origins east of the Lesser Antilles was at first believed to be a fiction resulting from the easier detection of storms affecting the dense net of observing stations in this island chain. Further study of storm origins has, however, modified this belief.

Figures 2 through 10 show in a somewhat different fashion the origin points of North Atlantic tropical storms and hurricanes. The portion of the storm track shown is from its earliest known, or suspected, point of closed circulation (open circle) to the point of hurricane intensity (solid circle). If the storm did not reach hurricane intensity, the birthplace is shown as an open circle with no track. The numeral within the circle represents the year in which the storm occurred.

As shown in figure 2, all June developments in the past 59 years were in the Gulf of Mexico or the western Caribbean, with the exception of three storms, one at low latitudes in the Atlantic and two in the Bahamas. No

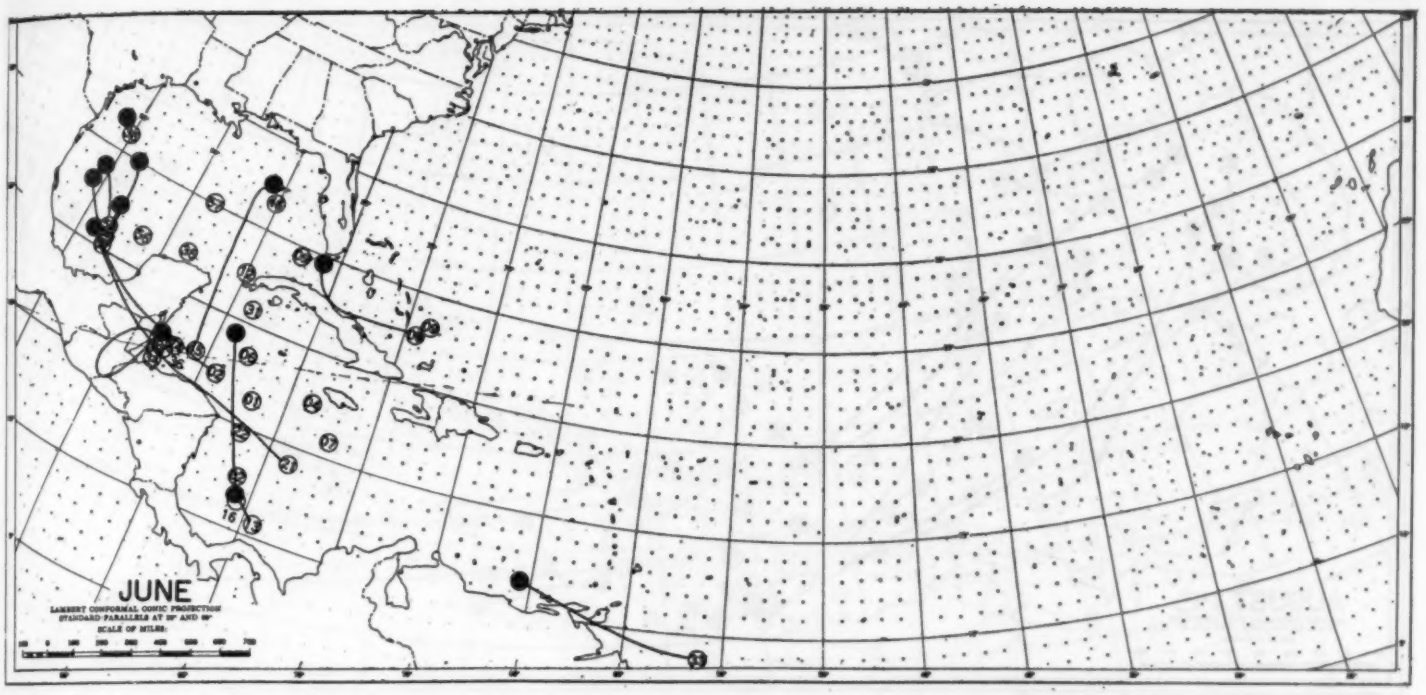


FIGURE 2.—Areas of storm development for June, 1899–1957. Open circle shows area of origin; solid circle, start of hurricane stage.

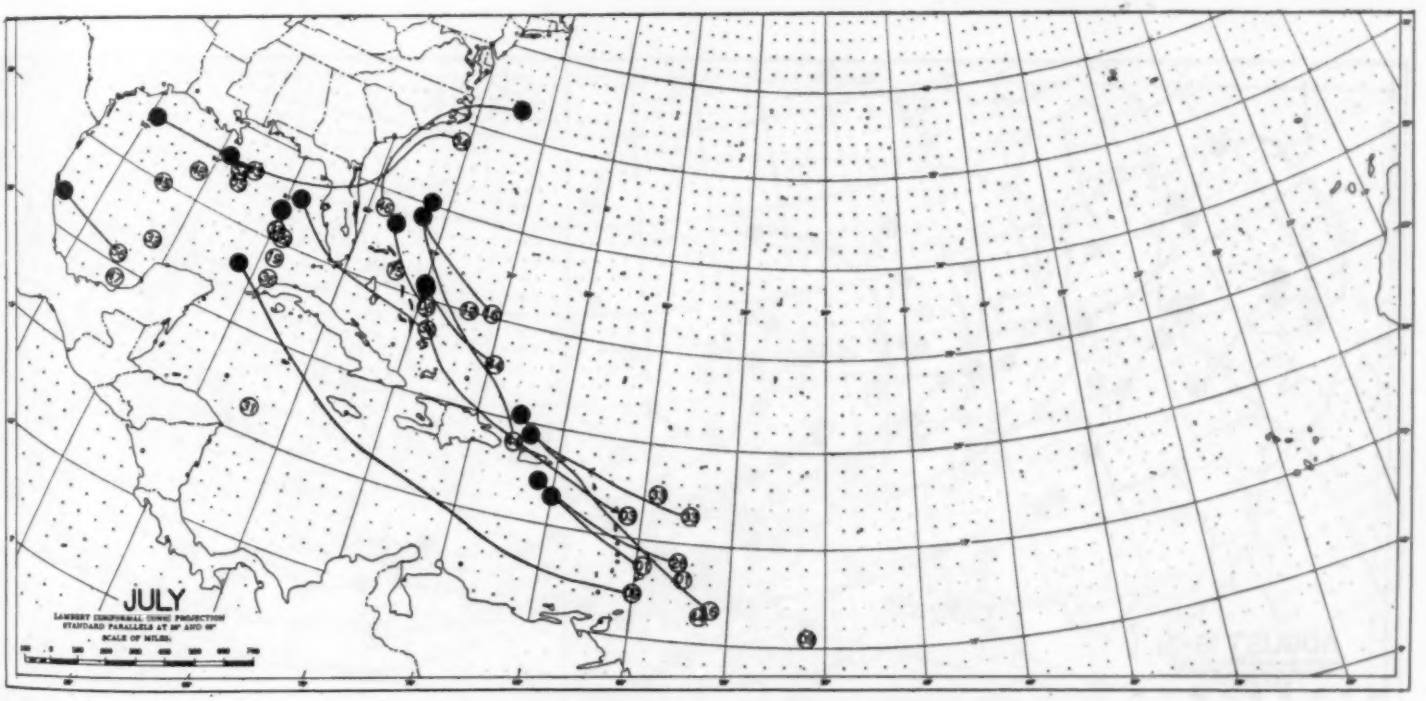


FIGURE 3.—Areas of storm development for July, 1899–1957.

birthplaces were detected east of 55° W. Tropical storms outnumbered hurricanes.

For July (fig. 3), the principal breeding ground shifted away from the western Caribbean. Tropical storms and a few hurricanes originated in the Gulf. The activity was greater than that of June in the Bahamas area and the region east of the Lesser Antilles. In July no birthplaces were detected east of 50° W.; the July origins were, however, well east of the June ones.

For early August (fig. 4), there were fewer origins in the Gulf. Most storms developed in the area just east of the West Indies and several originated (at about latitude 15°) over the Atlantic.

In the latter half of August (fig. 5), the main concentration of development was in the strip from the Bahamas southeastward to 15° N., 50° W., thence between 10° N. and 15° N. eastward to Africa. A large percentage of these storms reached hurricane intensity after only a very short travel over tropical waters.

For the first half of September (fig. 6) more storm

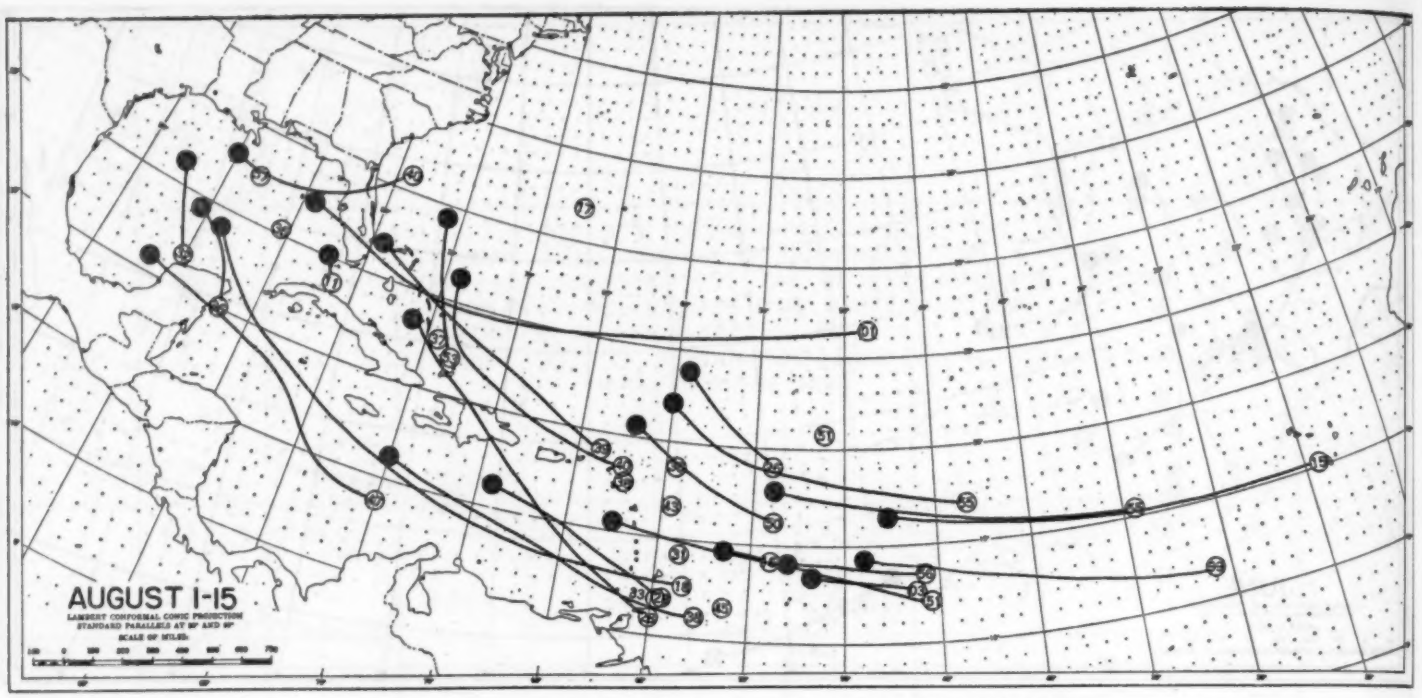


FIGURE 4.—Areas of storm development for August 1–15, 1899–1957.

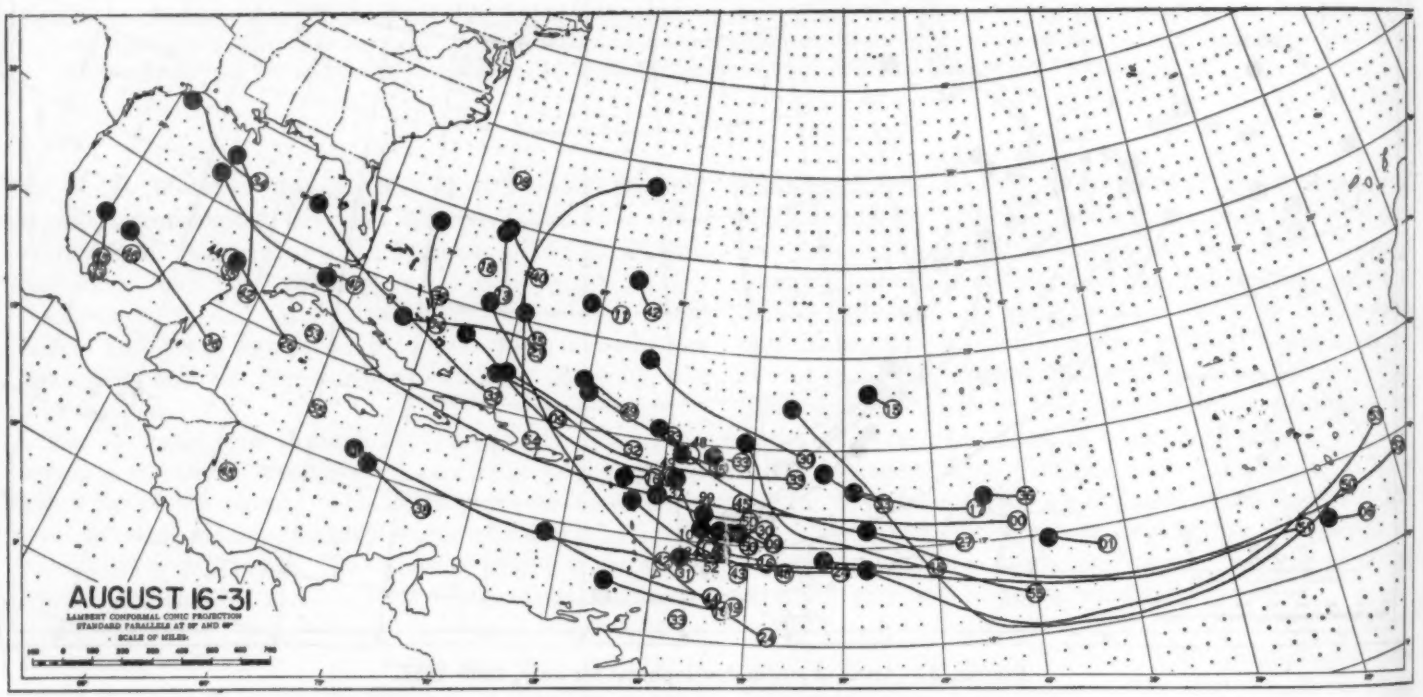


FIGURE 5.—Areas of storm development for August 16–31, 1899–1957.

originated in low latitudes over the eastern Atlantic, and again the development stages were frequently quite short. A number of storms which attained only tropical storm intensity developed in the southern Gulf, and quite a few circulations started at approximately 55° W., with a considerable northward component to their motion during development.

In the last half of September (fig. 7), with the total number of origins decreased, no storms developed so far east as in the early part of the month, and more storms formed at higher latitudes over the western part of the ocean. Developments were again frequent in the western Caribbean and southern Gulf areas, but much less frequent in the area just to the east of the Antilles than in the previous 30 days.

In early October (fig. 8), the densest concentration of

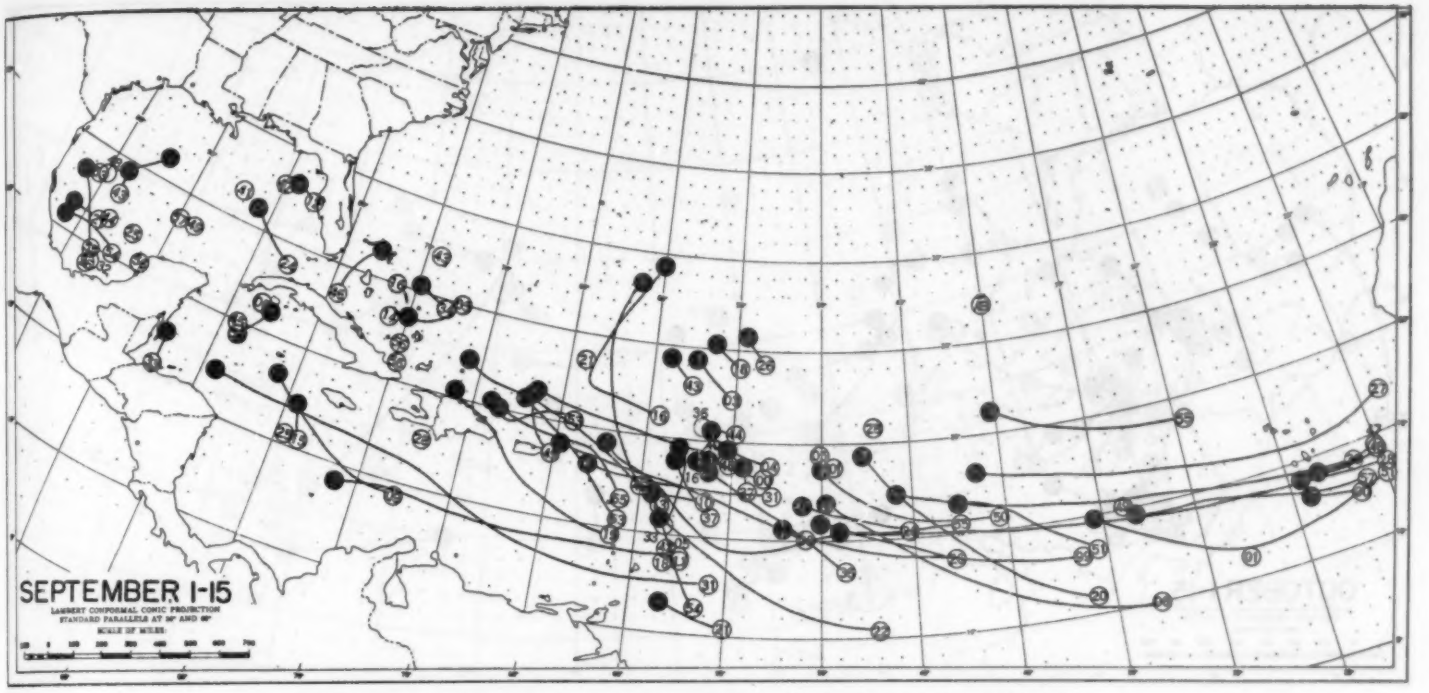


FIGURE 6.—Areas of storm development for September 1–15, 1899–1957.

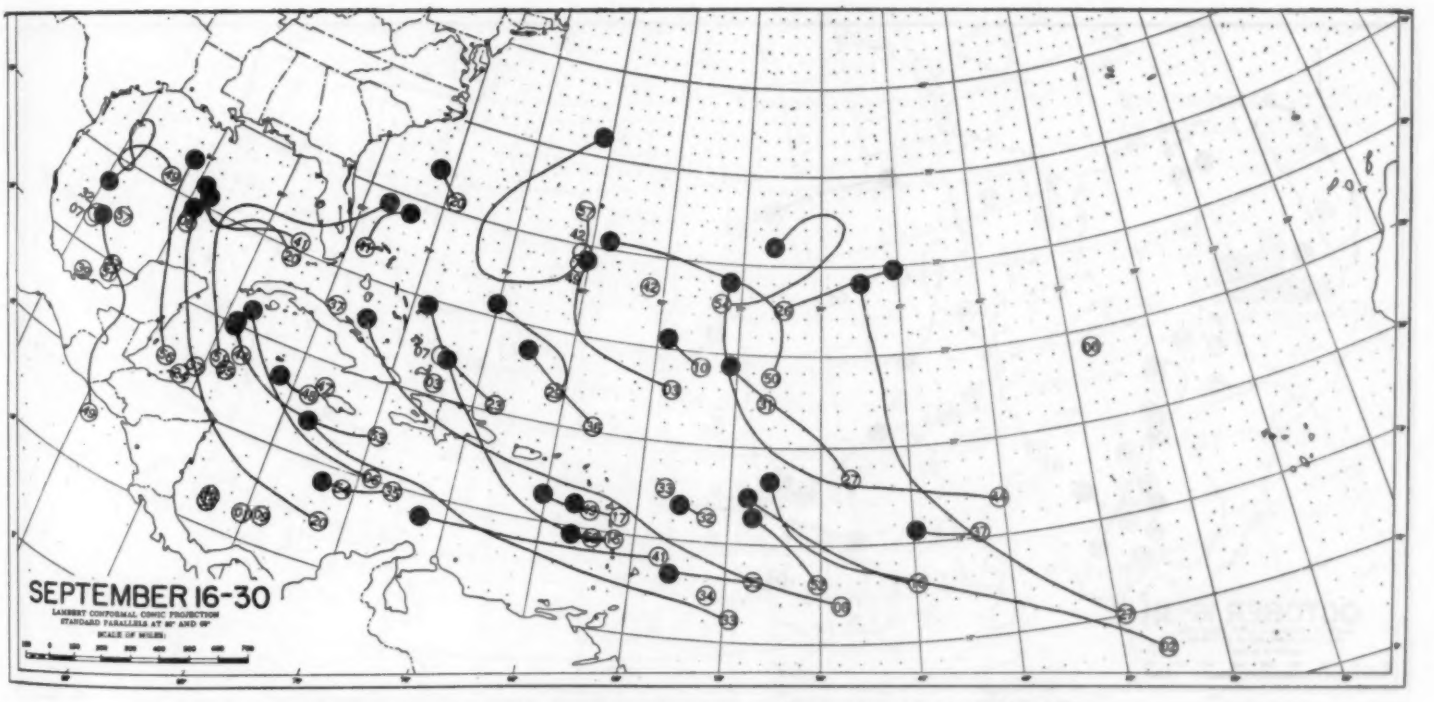


FIGURE 7.—Areas of storm development for September 16–30, 1899–1957.

origins was in the western Caribbean. Developments over the Atlantic were spread over a broad region west of 35° W. and ranging from 11° to 30° N., with one tropical storm in 1913 beginning at 40° N. This storm moved southward and later southwestward to enter the United States coast near Charleston, S. C. A few storms developed in the lesser Antilles and two which had their birthplace in the eastern North Pacific crossed the Central American Isthmus to enter the Gulf of Mexico.

For the latter half of October (fig. 9), storm activity, greatly reduced in all areas, was mainly in the western Caribbean-Yucatan area. Several tropical storms were spawned over the western Atlantic between 20° N. and 30° N. and two, in 59 years, originated in the Gulf.

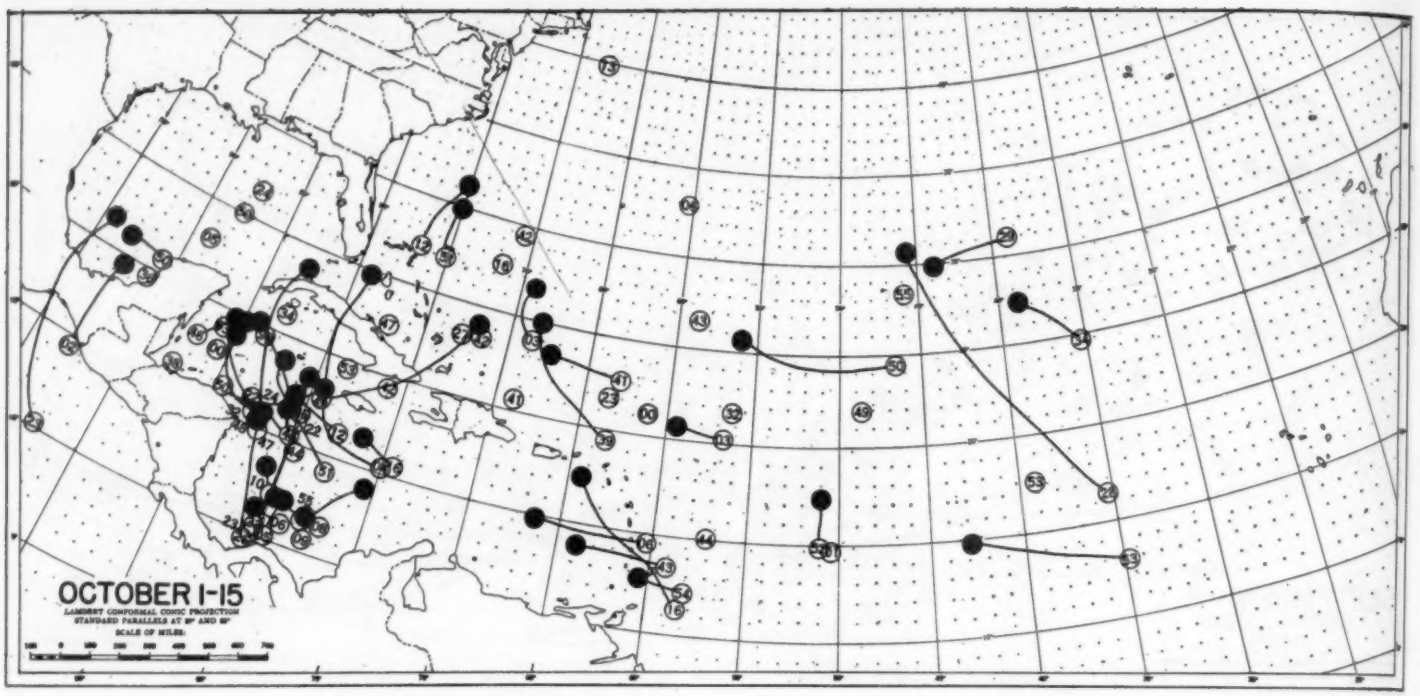


FIGURE 8.—Areas of storm development for October 1–15, 1899–1957.

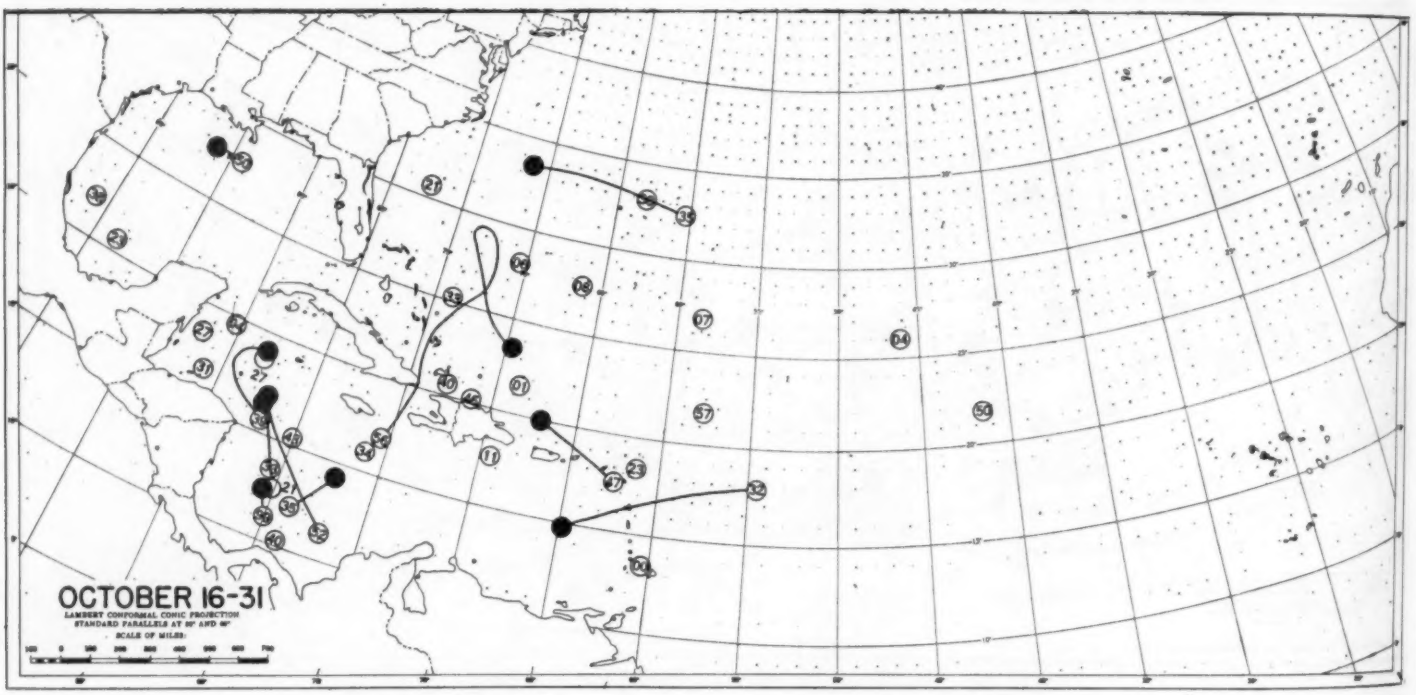


FIGURE 9.—Areas of storm development for October 16–31, 1899–1957.

For the colder months November through May (fig. 10), origins in this period were scattered over the ocean area northeast of the West Indies and in a concentrated area over the western Caribbean.

4. SUMMARY

The familiar shift from the western Caribbean in June gradually eastward in July and early August to the zone extending across the Atlantic in September and back again to the western Caribbean in the late season is obvious. A few early-season and many September storms have originated over the Gulf of Mexico.

The seasonal maximum of origins east of the lesser Antilles may be real, and not, as had previously been

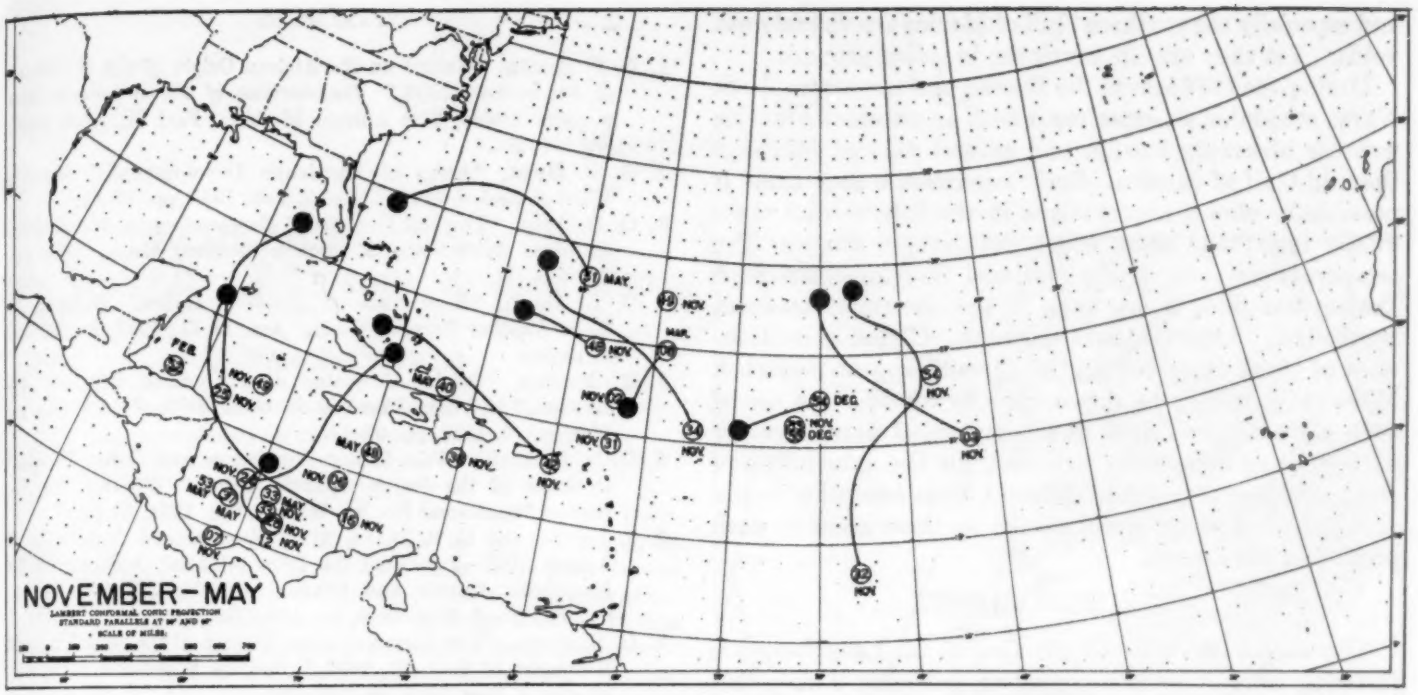


FIGURE 10.—Areas of storm development for November–May, 1899–1957.

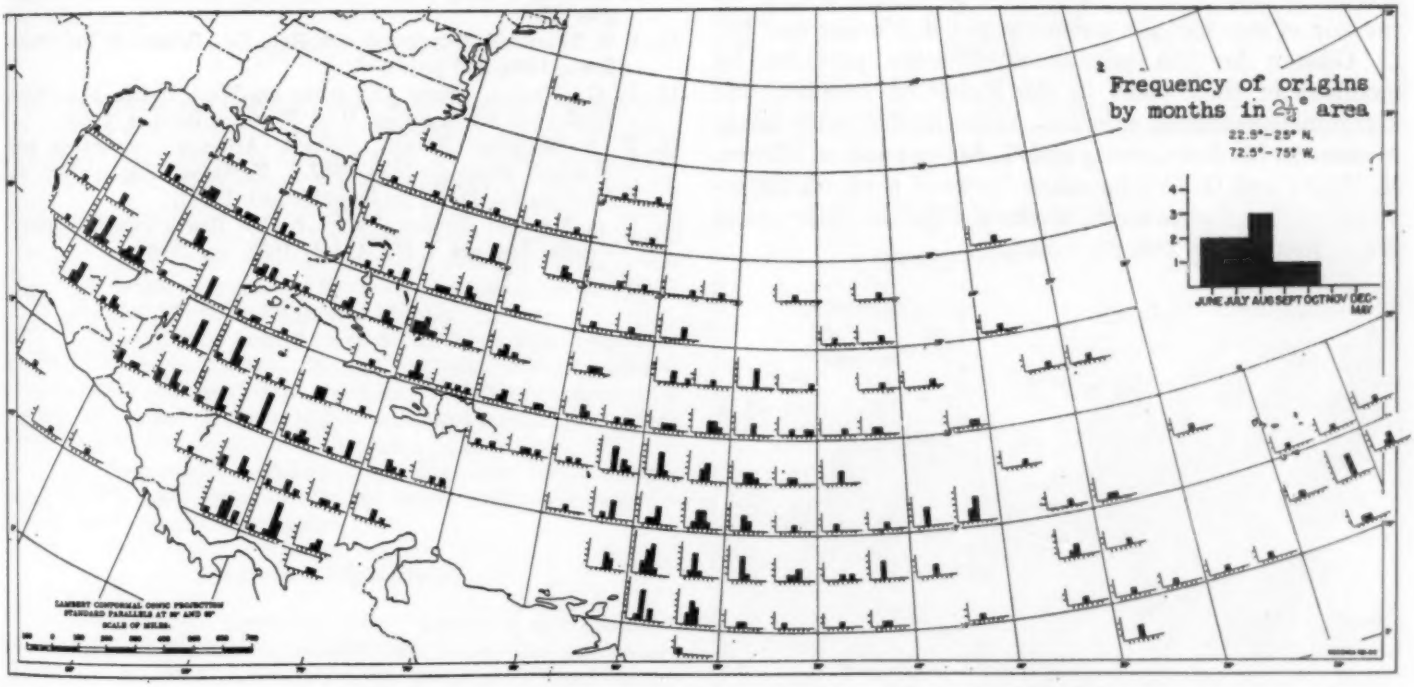
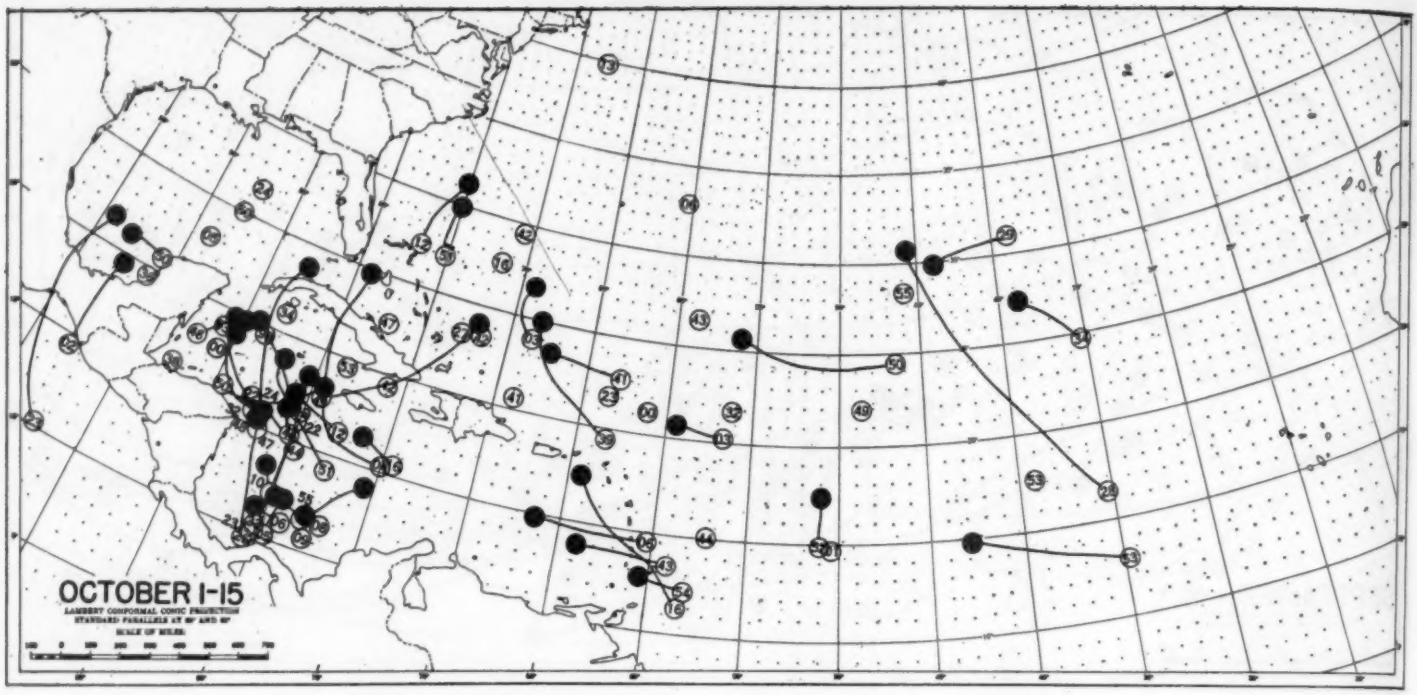


FIGURE 11.—Frequency of storm origins by months within 2½° areas (1899–1957).

believed, the accidental result of a denser net of observational points. The regular shift eastward and later westward through this region may explain the large maximum found here.

Figure 11 summarizes the origin data of figures 2–10 and shows schematically by months the frequency of storm origins over the North Atlantic, the Caribbean, and the Gulf of Mexico. This chart appears to support the conclusions of Mitchell [6] that the eastern Caribbean is not a birthplace of such storms.

Many of the tropical storms and hurricanes that have affected the United States had their beginning in areas where a minimum of meteorological observations have been available. The eastern Atlantic, the western Caribbean,



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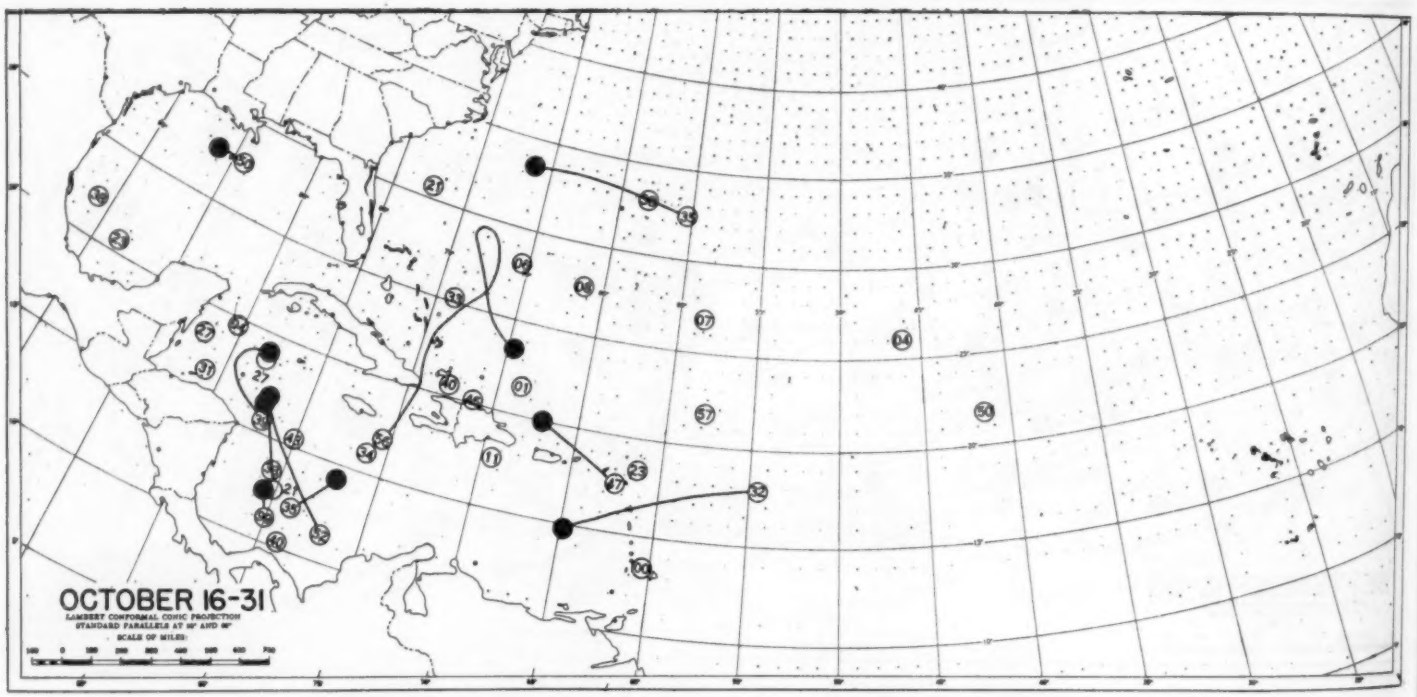

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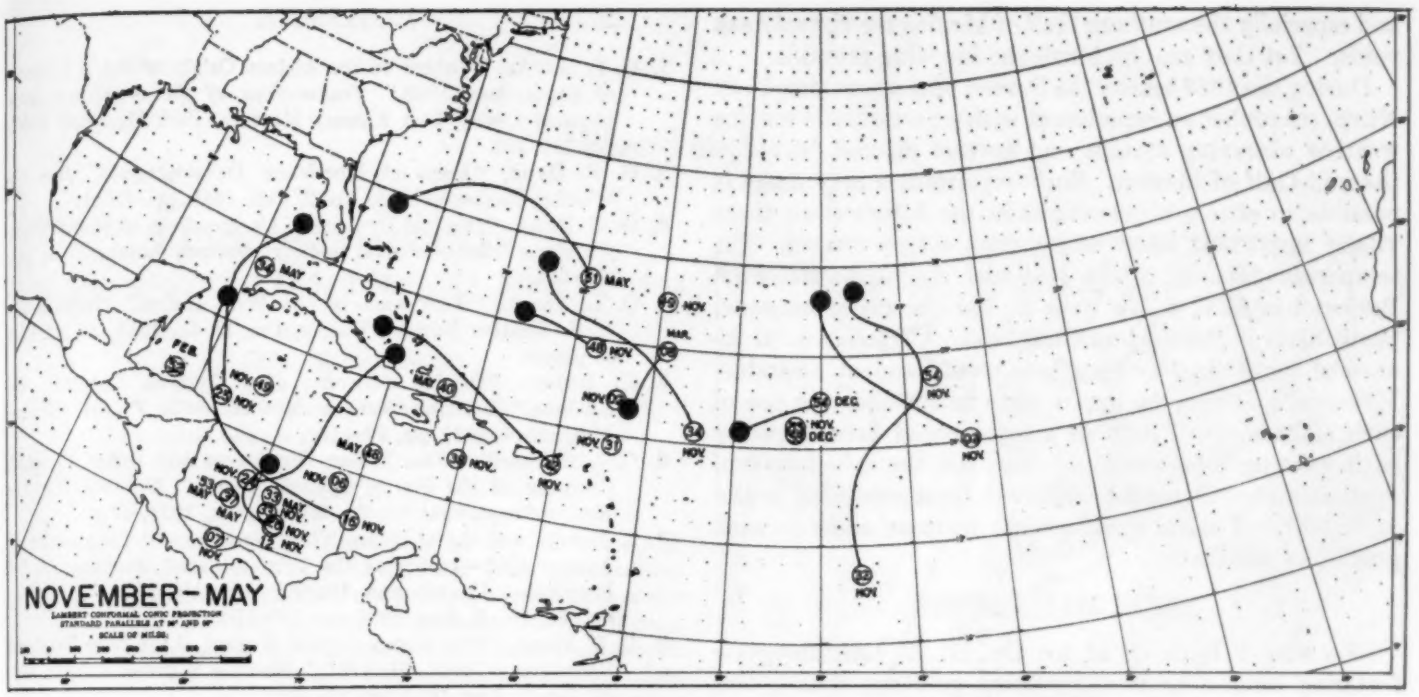

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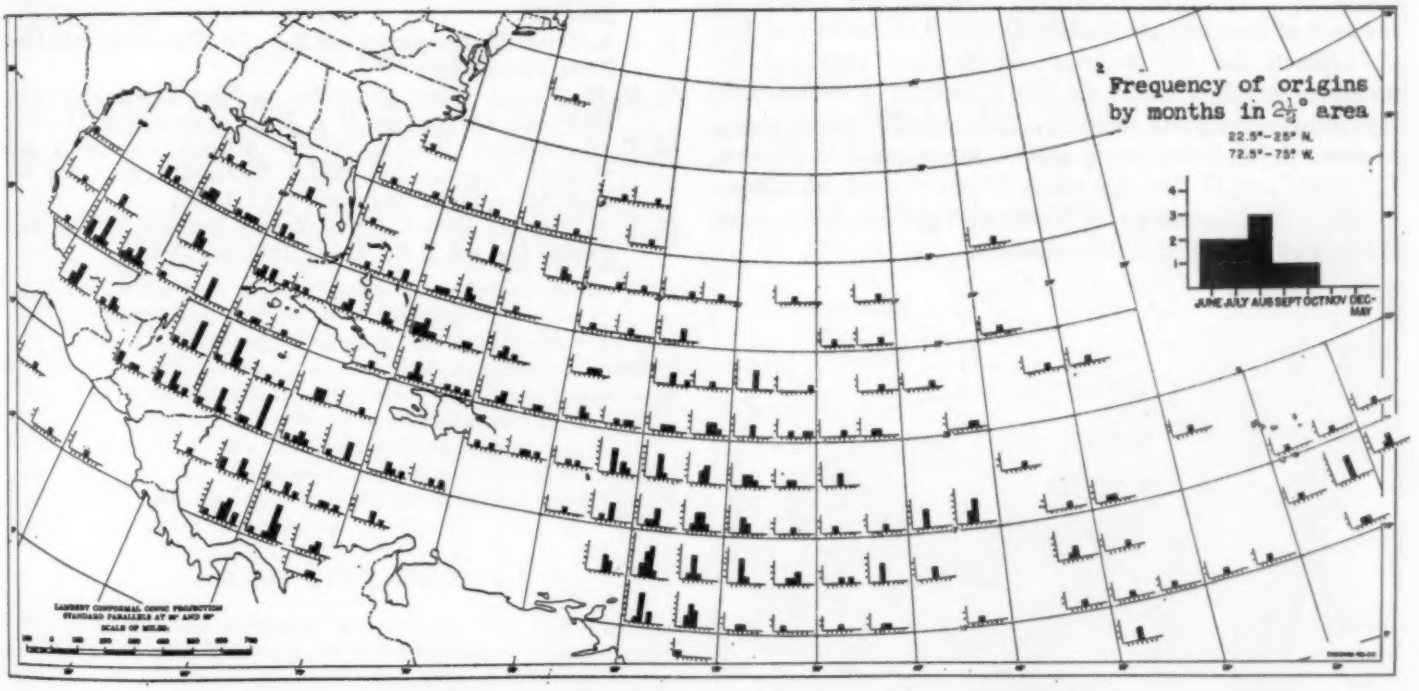

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Many of the tropical storms and hurricanes that have affected the United States had their beginning in areas where a minimum of meteorological observations have been available. The eastern Atlantic, the western Caribbean,

and especially the southern Gulf of Mexico are virtual data voids. Yet they are the hurricane breeding grounds.

During the 1958 season the Bureau of Aeronautics, U. S. Navy, scheduled an experiment with an automatic marine weather observing station and several moored buoys in the mid-Gulf of Mexico. Such experiments may make it possible to obtain observations in the future from these vitally important areas where data are so scarce. The temporary network of the National Hurricane Research Project has filled a few gaps in the observing network, particularly in the western Caribbean. Certainly continuance of these observing stations would appear desirable. Meanwhile, it may be appropriate to consider the use of such climatological data as are presented here, together with existing long-wave patterns, for the scheduling of reconnaissance flights into different areas according to the probability of storm development in these areas in each portion of the season.

ACKNOWLEDGMENTS

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Weather Note

RADAR OBSERVATIONS OF THE EL DORADO, KANS. TORNADO, JUNE 10, 1958

ALEXANDER SADOWSKI

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[Manuscript received July 17, 1958; revised October 27, 1958]

1. INTRODUCTION

This note on the tornado that struck El Dorado, Kans., on June 10, 1958, deals primarily with the radar scope presentations of the cloud echo and is based on the personal observations of the author who was operating the WSR-3 radar at Weather Bureau Airport Station, Wichita, Kans. A sequence of radar photographs and a description of radar features observed but not photographed are presented. A well-formed hook of short duration in the right rear quadrant of the echo is one of the main features evident in the photographic sequence.

The presentation of the radar observations is preceded by a brief summary of the synoptic conditions with which the storm was associated.

2. SYNOPTIC FEATURES

The correct interpretation of radar scope presentations and their use in issuing weather forecasts and warnings require the radar observer to be thoroughly familiar with the concurrent synoptic weather picture. The salient synoptic features of the June 10, 1958, storm situation are summarized in figure 1. At the surface was a low pressure trough with a slowly moving cold front across eastern Kansas. Ample moisture for convective activity was available at low levels over eastern Kansas as evidenced by dew point temperatures of 12° C. and higher at 850 mb.

At the 700-mb. level overriding cooler air in a bubble High that developed over northwestern Kansas and moved southeastward contributed to the instability of the air. Instability indices were exceptionally large. Another important feature was the strengthening of the jet level winds over Oklahoma and Kansas.

All of these synoptic clues to a developing severe weather situation served to alert the author to the necessity for maintaining a vigilant watch on the radar scopes.

3. RADAR OBSERVATIONS

The echo that was associated with the tornado first attracted attention at WBAS, Wichita, at 1540 CST because of its rapid intensification. At that time, the cloud was centered 37 n. mi. to the north-northwest of Wichita and was visible from the Weather Bureau office as a towering cumulus cloud with vigorous development of its "cauliflower top."

During the next hour (1540–1640 CST) the cloud moved in a general easterly direction with a speed of about 17 knots. About 1643 CST a notch or indentation appeared on the far side of the echo (in relation to the radar station) and the storm changed to a southeastward direction of movement; the trailing portion of the echo nearest the station moved at a speed slightly exceeding 20 knots.

Figure 2 displays a sequence of photographs of the Plan Position Indicator (PPI) scope. The 1650 CST photograph shows the fading notch on the northeast side of the echo and the beginning of a hook appendage in the right rear quadrant of the echo.

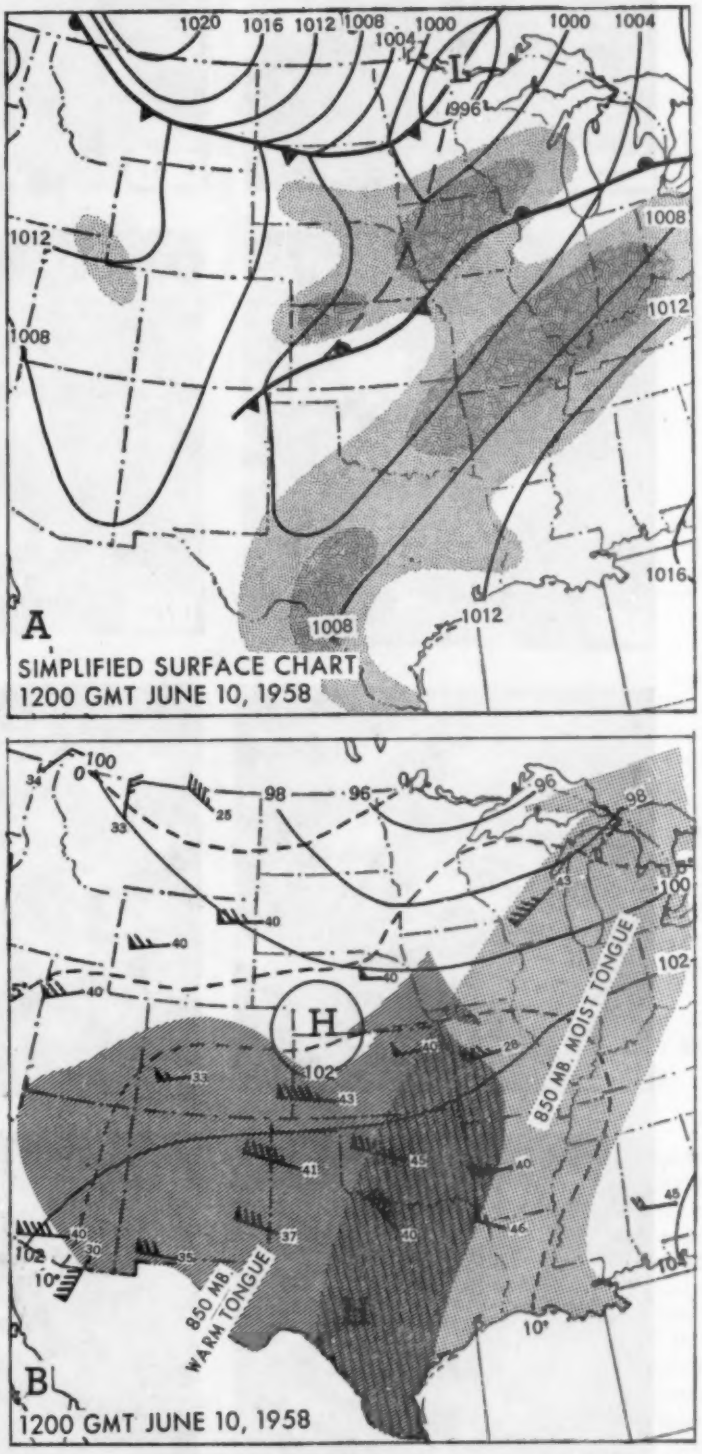

Figure 1.—Synoptic situation at 1200 GMT, June 10, 1958. (A) Surface isobars and fronts with area of negative stability index shaded. Darker shading indicates values of −4 and lower. (B) 700-mb. contours and isotherms with 850-mb. warm and moist advection indicated by shading. Winds are for jet level with height given in thousands of feet.

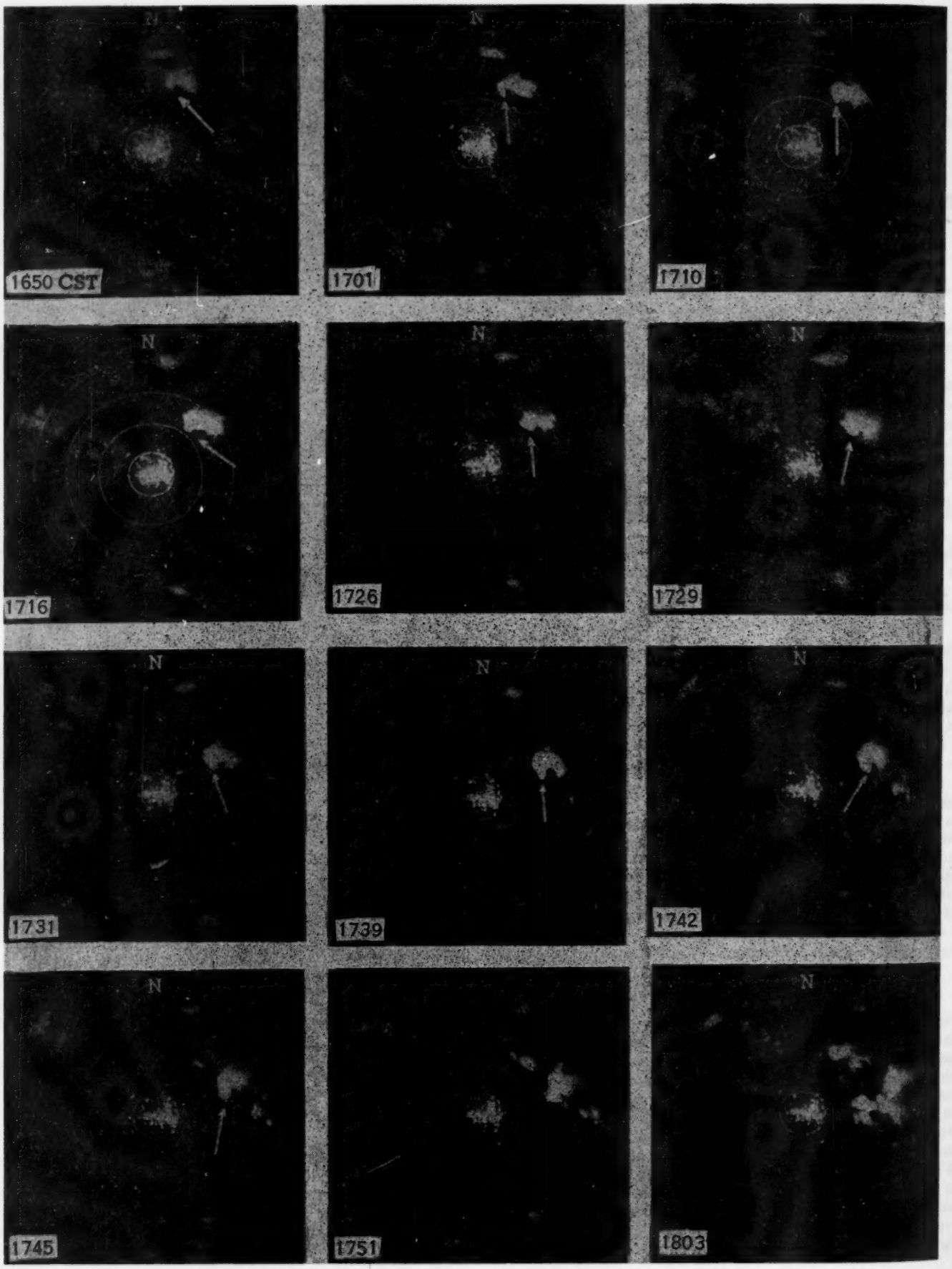

Figure 2.—Radar PPI scope photographs taken at WBAS Wichita, Kans., on June 10, 1958 during time of tornado at El Dorado, Kans. Range is 50 n. mi. (10 n. mi. between rings) and antenna elevation 0°.

The 1701 CST photograph shows the most pronounced appearance of the hook on the echo. Because illumination from the last sweep of the antenna (rotating at 4 revolutions per minute) was still faintly visible during observation as each new sweep moved across the echo, it was possible to see the growth of the echo in a cyclonic sense to form the hook. Such an observation of echo growth between sweeps would be discernible only in cases of very rapid echo development. A rough computation of the advance of the echo's formation by the observable movement and development gave a speed of about 300 knots. This observation is another that can be added to the already many films indicating the circulation of the hook actually to be cyclonic in nature and not a divergent outflow.

The duration of an easily identifiable hook was the short time of about 15 minutes. While the hook was evident the State police were asked to investigate the storm associated with the echo. Their report was that no tornado or funnel was observed, although it was raining with some hail in the area of the hooked echo. At 1720 CST a report was received that White Water (see fig. 3) had hail up to 3 inches in diameter but little rain and wind. The hailstorm was coincident with the radar echo.

The 1726 CST picture shows no evidence of a hook; only a slight protrusion still existed. At 1729 CST the sharp-edged protrusion was still plainly visible. At this time eyewitnesses at the El Dorado Interchange on the Kansas Turnpike spotted a funnel-shaped cloud about 3,000 feet up and about 7 miles to their west (see fig. 3). This position was coincident with the radar echo.

The 1735 CST photograph shows that the protrusion was still plainly visible and by 1739 CST it became even more plainly defined by its sharp-edged hard appearance. The protrusion gradually merged with the main cell and by 1751 CST was no longer identifiable. Shortly thereafter, at about 1755 CST, the tornado "pumped" down from the parent cloud on the outskirts of El Dorado at the approximate location given in figure 3. The information about the tornado "pumping" action was given by a survivor of the devastated area of El Dorado who had a good view to the west across an open field. He saw the tornado "pump" down to the ground while the cloud was over the Midian Substation on the western outskirts of El Dorado. Each successive "pumping" action lowered the funnel until it contacted the ground. There was a light sprinkle of rain falling from the cloud between the survivor and the funnel.

When he saw the funnel touch the ground, the survivor and his family went to the basement of their home, which about 2 minutes later was destroyed by the tornado. All were safe, as indeed were all the residents of this street; they, too, had gone into their basements and survived the destruction of their homes.

Another eyewitness account of the tornado's approach to El Dorado was given by a State Highway Patrolman, Mr. Robert Lemon, who made positive identification of the tornado approaching the southwestern section of El Dorado. Following is Mr. Lemon's statement:

"I was observing a Wichita television program at my home shortly before coming on duty at 1700 CST. The television program was interrupted to give a severe weather bulletin. [SELS Severe Thunderstorm forecast No. 127 issued at 1630 CST included this area as subject to severe thunderstorms with isolated hail and damaging wind storms.] The sky looked very ugly with thunder and lightning in the distance, heavy clouds, rather still surface conditions, and very hot. The Weather Bureau has furnished informational material on tornadoes, and State Headquarters has insisted that all patrolmen study this subject. I was driving north about ½ mile north of the Skelly Oil Refinery on the Kechi-Towanda road, when to my amazement, I saw a straight-sided column of whirling mass extending from the base of the cloud to the ground. This column was white in color and was moving from the northwest to the southeast at quite a rapid rate. I immediately radioed the Chief of Police, the El Dorado Sheriff, and the Highway Patrol District Headquarters in north Wichita. Flying debris in advance of the tornado began closing my path. I had to stop and back up and take another route into El Dorado. I radioed my observation at 1755 CST. [This time confirmed by north Wichita Headquarters communication log.] The tornado funnel traveled almost in a U shape, approaching from the northwest, turned to straight west, and was changing to a southwesterly direction when it lifted back up into the clouds."

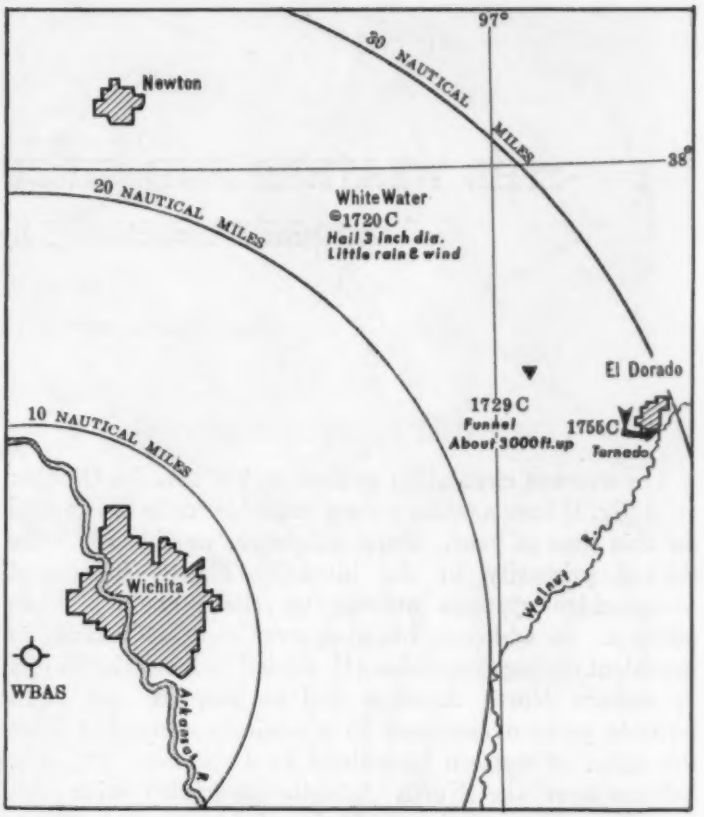

Figure 3.—Map of Wichita-El Dorado area.

The tornado made a U-shaped path, with the bottom portion of the U being the west-to-east path through southwestern El Dorado as shown in figure 3. In the right portion of the U the funnel was described as withdrawing into the cloud.

The tornado destroyed or damaged some 150 homes, injured 50 persons, and killed 15. Property damage was estimated at $3 million.

4. CONCLUSIONS

The true hook of the cloud associated with the El Dorado tornado was viewed by radar as a cyclonic swirling of the cloud echo into a hook-shaped appendage. The duration of the identifiable hook was only about 15 minutes. This leads to the conclusion that to catch the formation of significant "hooks" on radar echoes the radar operator must observe the scopes continuously during a severe storm situation; otherwise he may miss the hook completely or, if he observes it, be unable to tell whether the appendage is a true hook. If further experience with radar echoes shows that, as in this case, hooks appear well in advance of tornadoes, it may be possible in favorable circumstances to issue advance warnings on the basis of the PPI scope presentations before the tornado drops from the clouds. However, in other cases, additional means, such as visual sightings, Doppler radar, or sferics, are necessary to supplement radar PPI scope observations for the quick identification of tornado-producing formations.

THE WEATHER AND CIRCULATION OF OCTOBER 1958[1]

A Month Characterized by a Pronounced Index Cycle

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1. MONTHLY MEAN CIRCULATION

The average circulation pattern at 700 mb. for October 1958 (fig. 1) bore a rather strong resemblance to the normal for this time of year. Such differences as did exist were related primarily to the intensity of the individual trough-ridge systems making up the planetary wave pattern. In addition, blocking over central Canada, so prevalent during September [1], tended to shear the trough in eastern North America and to displace the high-latitude portion eastward to a position extending from the coast of western Greenland to Labrador. 700-mb. heights over the North Atlantic associated with this trough were as much as 250 feet below normal (Inset, Chart XI). Blocking in central Canada could also be related to the appearance of a high-latitude ridge in that area, while the major ridge over North America extended from western Canada southward, close to its normal position (fig. 1). Strong ridging in mid-Pacific was associated with a large area of positive anomaly, in marked contrast to September [1] when 700-mb. heights in the same area were slightly below normal. The Low centered over the North Pole in September deepened strongly in October as it moved to the Pacific side of the Pole. The negative anomaly (−420 ft.) associated with this polar vortex was the largest anomaly of either sign to appear on the mean 700-mb. map for October.

Of interest is the fact that the zonal index, a measure of the net geostrophic west wind flow from 55° to 35° N. in the Western Hemisphere, continued above normal during October. This index, as derived from the monthly mean 700-mb. charts, has not been below normal since mid-spring 1958 [2] (table 1). It is important to note, however, that while the indices for August and September were both well above their normal values, October's index was only slightly above normal. This was related to a pronounced index cycle which occurred during October and interrupted, at least temporarily, the extended period of fast westerlies.

2. THE INDEX CYCLE

The index cycle which occurred is shown graphically by figure 2, which gives the time variation of the 5-day mean 700-mb. zonal index plotted thrice-weekly at the middle day of each period. It is evident from the graph that the mid-latitude westerlies did not fall below normal until just after mid-October and remained below normal until the end of the month. Thus, consideration of selected aspects of the general circulation on a 15-day basis should portray characteristics commonly associated with the high and low stages of an index cycle [3].

TABLE 1.—*Monthly mean values of 700-mb. zonal index (in meters per second) in the Western Hemisphere during 1958*

Month	Index	Normal	Anomaly
April	7.9	8.3	−0.4
May	8.0	7.7	+0.3
June	7.3	6.9	+0.4
July	7.8	7.2	+0.6
August	8.6	6.8	+1.8
September	9.3	7.8	+1.5
October	9.8	9.5	+0.3

Let us examine first the 15-day mean 700-mb. charts and height departures from normal for both halves of October (fig. 3). The zonal indices for these half-months were 11.3 m. p. s. and 8.3 m. p. s. Note particularly the strong zonal character of the flow pattern and anomaly fields in the Western Hemisphere during the first half of the month. In addition, strongest cyclonic activity was confined to the higher middle latitudes, and the meridional exchange of energy was kept to a minimum. Now contrast this flow pattern with that for the latter half of the month. Note the change to more meridional flow and the appearance of two strong positive anomaly centers over Canada and the North Atlantic. Concomitant with these anomaly centers was the extensive band of negative anomaly at lower latitudes, extending from the eastern Pacific to the Atlantic. Cyclonic activity then was much more frequent at lower latitudes, with several storms developing in the Gulf of Mexico. These disturbances moved very slowly up the mean trough along the Atlantic Coast (Chart X), being blocked by high pressure to the north. A particularly vigorous storm with pressures as low as 980 mb. developed in the central Atlantic, remaining stationary between latitudes 35° and 40° N. on the 23d and 24th.

The height change chart (fig. 3C) shows at a glance the magnitude of the circulation reversal which occurred near the middle of October. Greatest changes were in the North Atlantic and over Europe, where height changes

[1] See Charts I-XVII following p. 424 for analyzed climatological data for the month.

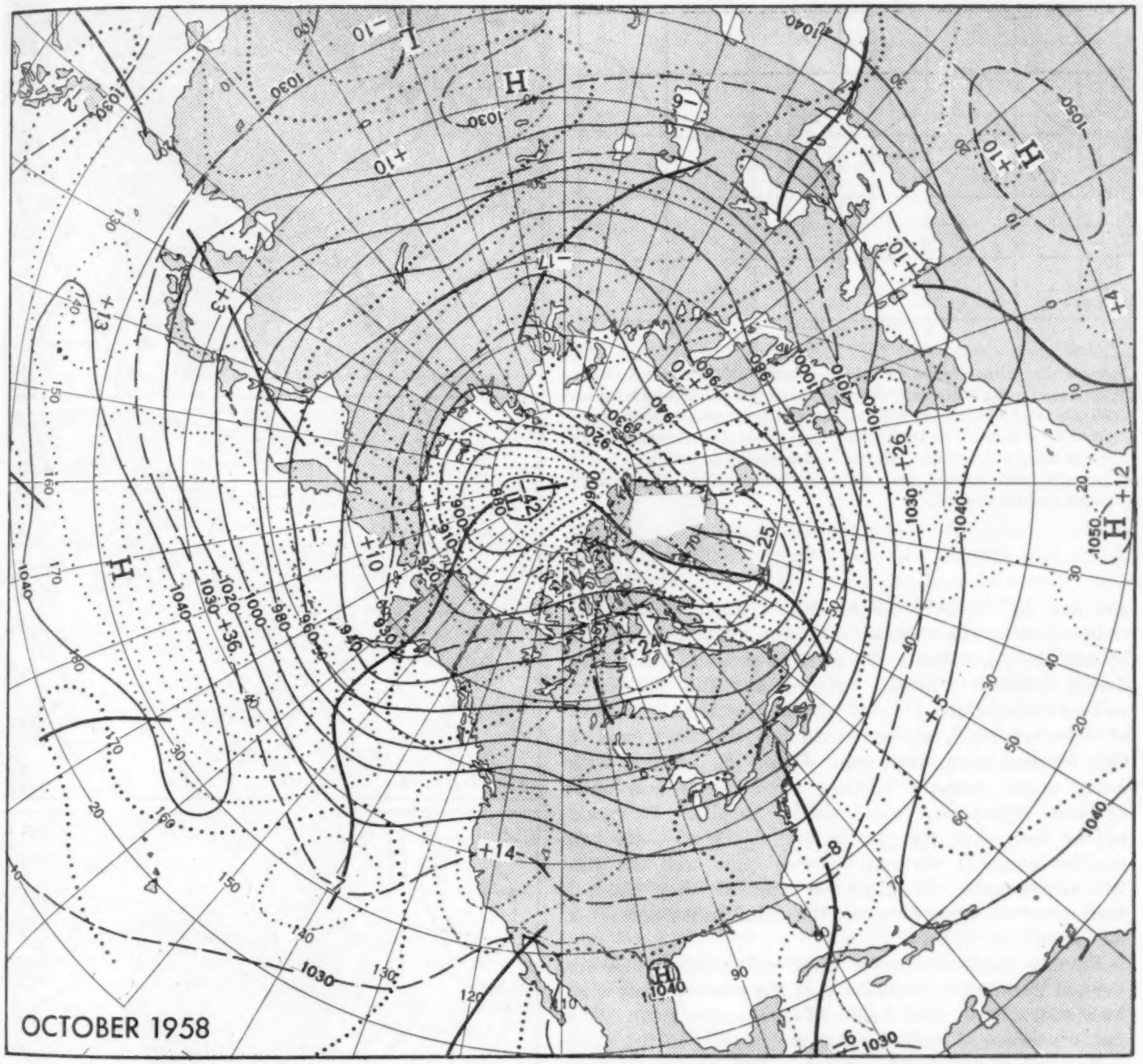

FIGURE 1.—Mean 700-mb. height contours (solid) and departures from normal (dotted) (both in tens of feet) for October 1958. Important circulation features in North America were stronger than normal ridge in the West, deeper than normal trough in the East, and blocking in Canada.

of as much as +780 ft. and −750 ft. occurred, respectively. These pronounced height changes were related to a complete reversal of the planetary trough-ridge system in those areas. Readjustments in the circulation also occurred downstream, with the Asiatic coastal trough deepening as it retrograded, while at the same time the polar low deepened and shifted its influence more toward northern Siberia. Deepening of the eastern Pacific trough was accompanied by height changes of as much as −560 ft. In North America 700-mb. heights rose over nearly all of Canada, while almost the entire United States experienced a change in the opposite sense.

Both the +400-ft. anomaly in Canada and the +520-ft. anomaly in the Atlantic (fig. 3B) were related to two strong blocks which appeared during the latter half of October. Tracks of the overlapping 5-day mean anomaly centers associated with these blocks are shown in figure 4. Note that the Canadian anomaly attained maximum intensity (+950 ft.) at 60° N., while the Atlantic anomaly reached its maximum (+850 ft.) at 55° N. The change in intensity of these anomaly vortices as they moved meridionally was in agreement with previous studies. Klein [4] has shown that the average annual pressure variability tends to be greatest near 60° N. over eastern Canada

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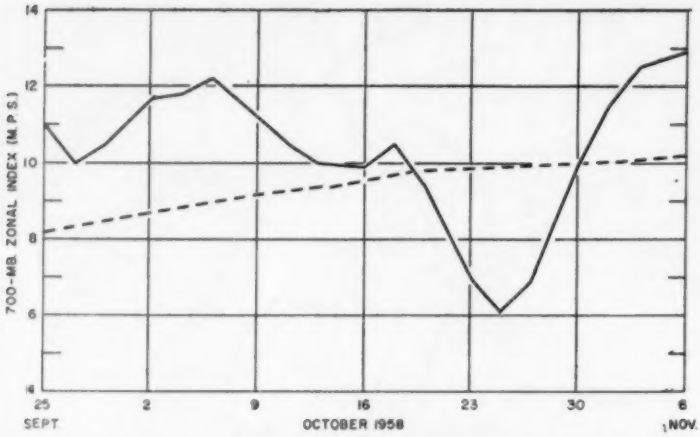

FIGURE 2.—Time variation of temperate-latitude zonal index (average strength of zonal westerlies in meters per second between 35° N. and 55° N.) at 700 mb. over the Northern Hemisphere from 0° westward to 180° longitude. Solid line connects 5-day mean zonal index values (plotted thrice weekly at middle of 5-day periods) and dashed line gives normal values. Pronounced index cycle is evident.

and near 55° N. over the Atlantic. Recently published charts showing the standard deviation of 500-mb. heights by months [5], indicate the greatest pressure variability during October is usually between 50° and 55° N. in eastern Canada and near 55° N. in the Atlantic. Both of these studies, however, were made without regard to sign (cyclone or anticyclone). Clapp [6], working with 5-day mean anomaly vortices for cyclones and anticyclones separately, found similar results. It would appear then that the growth and decay of these two positive anomaly vortices followed quite well the statistical averages. As might be expected, they reached their greatest strength when the zonal index was at a minimum (figs. 2, 4).

Further manifestations of the October index cycle are evident in the relative positions of the primary west wind axis at 700 mb. for both halves of the month (fig. 5). The fast westerlies of early October are implicit in the small latitudinal variation of the jet. With the onset near mid-month of blocking over Canada, the primary westerly jet split into two branches, one passing far north over Canada, the other over the Florida Peninsula. A marked northward displacement of the westerlies occurred in the Atlantic in connection with blocking in that area. Note also that the relative position of the Pacific jet remained nearly stationary during both halves of the month (fig. 5), with even stronger wind speeds prevailing during the latter half (not shown). Thus, the Pacific circulation remained of a high index character throughout the month.

Finally, a study of the 700-mb. zonal wind speed profiles for the Western Hemisphere for the two 15-day periods (fig. 6) reveals characteristics quite typical of an index cycle. For instance, note the sharply peaked profile with maximum wind speeds in excess of 14 m. p. s. for October 1–15. Contrast this with the rather blunt profile

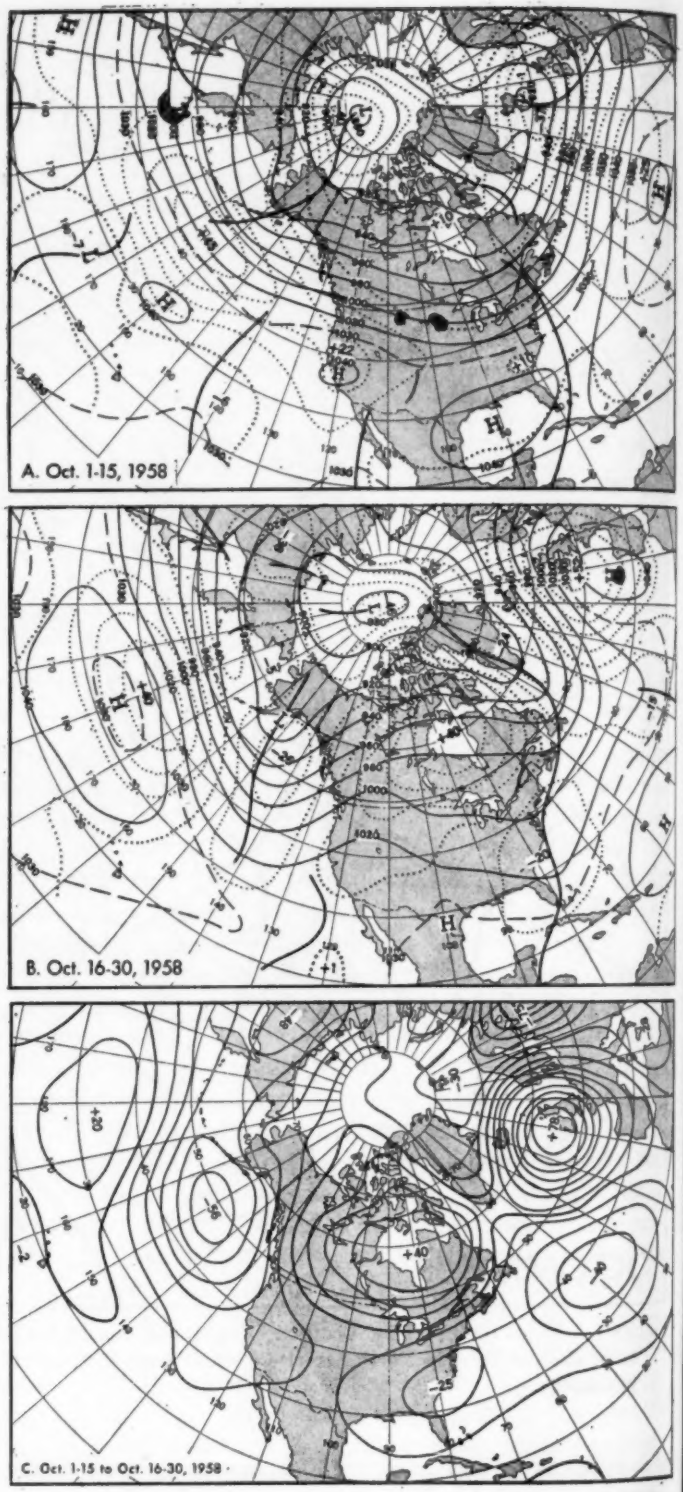

FIGURE 3.—Fifteen-day mean 700-mb. height contours (solid) and departures from normal (dotted) (both in tens of feet) for (A) October 1–15, 1958, and (B) October 16–30, 1958. (C) Height change (tens of feet) from (A) to (B). Onset of blocking in Canada and the North Atlantic accompanied major changes in the circulation.

for the period October 16–30, with middle-latitude wind speeds considerably weaker. Furthermore, both the polar and subtropical westerlies were stronger during the

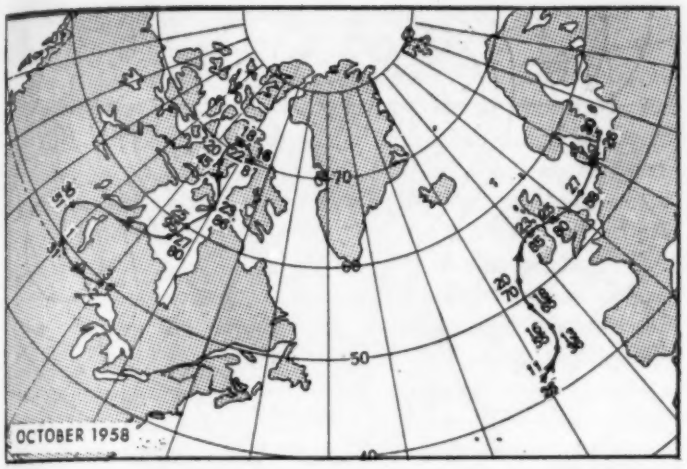

FIGURE 4.—Tracks of two prominent 700-mb. 5-day mean positive anomaly centers during October and early November 1958. Top number is middle day of period; lower number, intensity of center (tens of feet). Strong blocking was associated with these persistent anomaly centers.

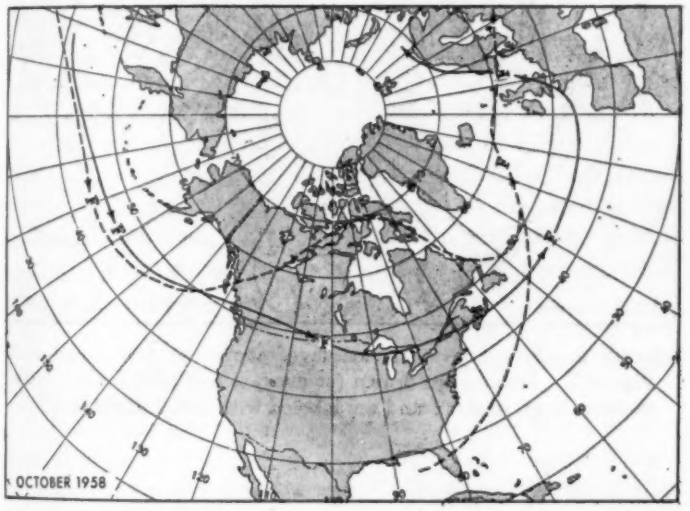

FIGURE 5.—Position of primary 700-mb. jet axes for October 1–15, 1958 (solid) and October 16–30, 1958 (dashed). Northward displacement of the mean westerlies over North America and the Atlantic near mid-October was an important feature of the circulation.

latter period, thus tending to conserve the total momentum of the westerlies [3].

Shorter-period means bring into even sharper focus the contrasting flow patterns associated with high and low index. In figure 7 is shown the 5-day mean 700-mb. charts observed at the times of highest and lowest zonal index. Important differences between the two charts are similar to those observed between the two 15-day mean charts (fig. 3), but are even more striking. Note the pronounced zonal flow and confluent nature of the circulation with high index. This is in sharp contrast with the cellular, difluent, and meridional flow pattern observed under low index.

Similar differences are also apparent on the corresponding sea level charts shown in figure 8. Note, in particular, the extensive high pressure area over Canada with center over Hudson Bay. Other outstanding differences were the appearance in the period October 23–27 of a strong anticyclone over Great Britain and a cyclone in mid-Atlantic. In general, sea level pressures (and 700-mb. heights) at time of low index were higher at high latitudes and lower at low latitudes than during high index. Extreme values of the daily zonal index during the month were 13.1 m. p. s. on October 1 and 7 and 5.7 m. p. s. on October 27.

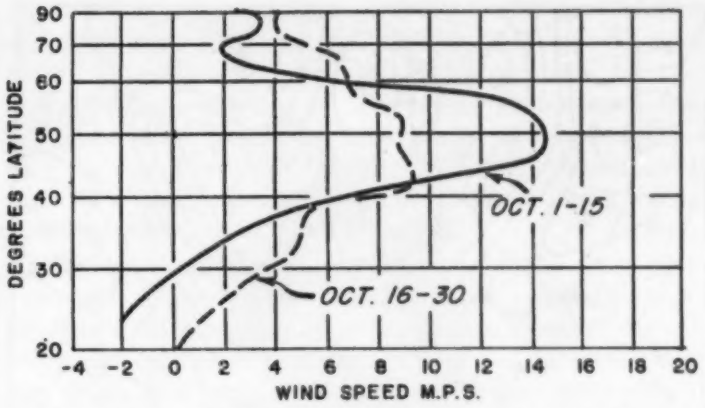

FIGURE 6.—Mean 700-mb. zonal wind speed profiles in the Western Hemisphere (0° westward to 180°) for October 1–15, 1958 (solid) and October 16–30, 1958 (dashed). Note diminution of temperate westerlies and increase in both the polar and subtropical westerlies after mid-month.

3. UNITED STATES WEATHER

Unusually fine fall weather prevailed over most of the Nation during October with few extremes observed. East and south of a line from New Mexico to New York temperatures averaged below normal, while west and north of this line temperatures were above the normal (Chart I–B). In general the pattern of 700-mb. height departure from normal (fig. 1) appears well correlated with the temperature anomaly pattern. However, in the middle of the country, despite near normal 700-mb. heights, temperatures ranged from 2° to 3° F. above normal in the Upper Mississippi Valley and western Lakes Region to as much as 6° F. below normal in southern Texas (Chart I–B). This apparent discrepancy can be related to stronger than normal northerly anomalous flow advecting polar airmasses from an abnormally warm source region in central Canada. These airmasses were associated with polar anticylcones (Chart IX) and were cooled (relative to normal) as they moved southward. In southern Texas part of the unseasonable coolness was a result of dynamic cooling associated with heavy precipitation.

Some of the coldest weather occurred early in the month when a deepening storm, moving in late September from the northern Plains to northeastern Canada, swept cold polar air into the country as far south as northern Florida.

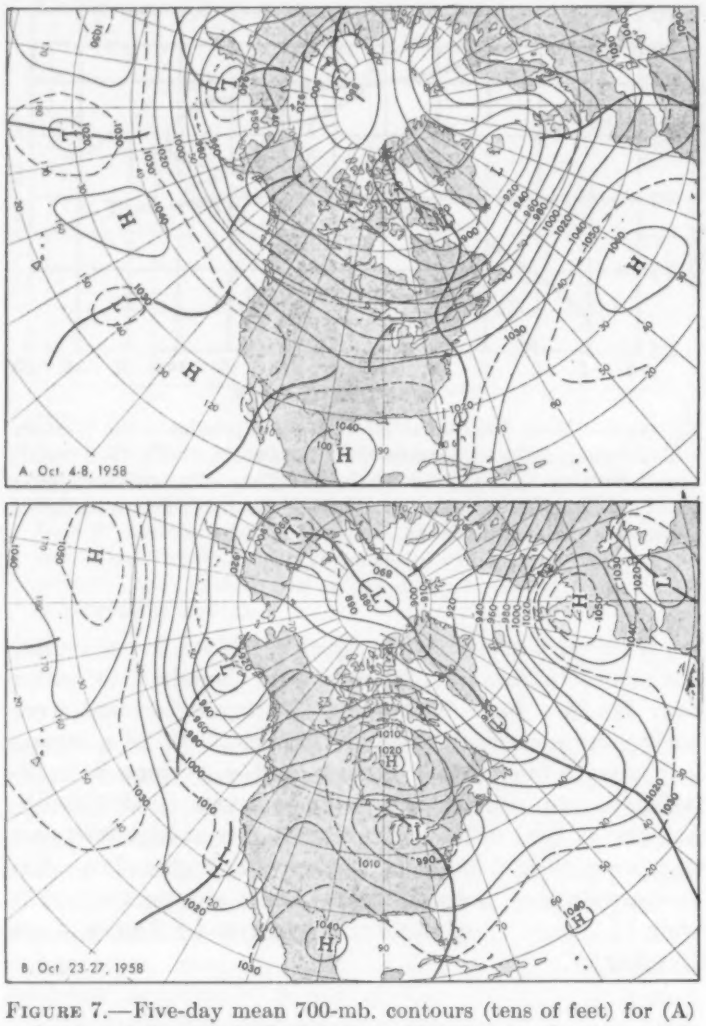

FIGURE 7.—Five-day mean 700-mb. contours (tens of feet) for (A) October 4–8, period of highest zonal index in October 1958; and (B) October 23–27, period of lowest zonal index in October 1958. Note change from zonal to meridional flow.

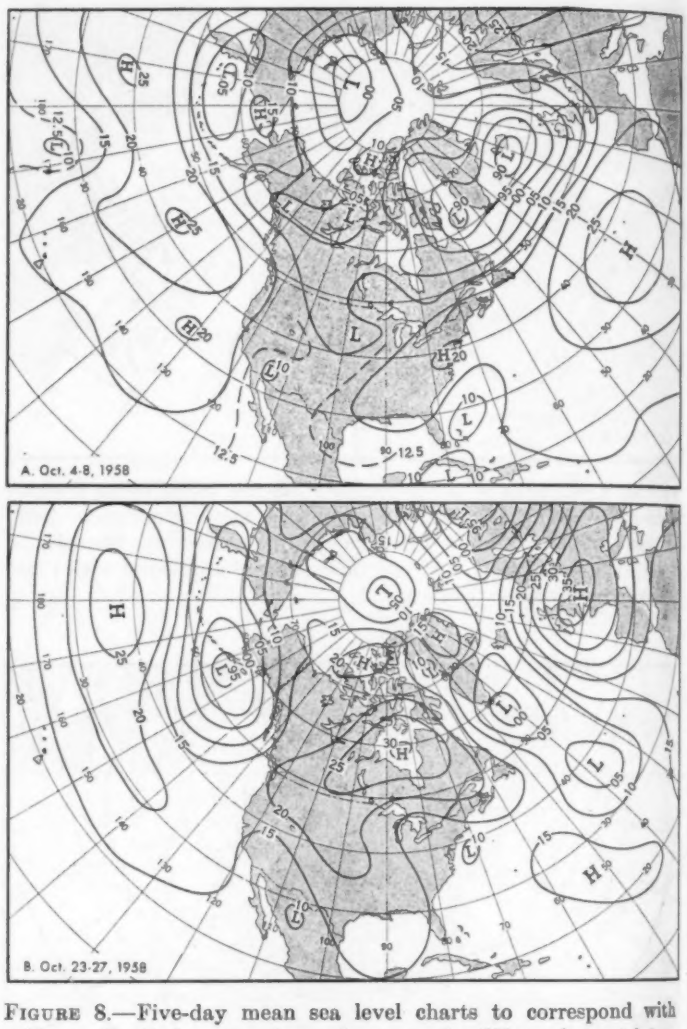

FIGURE 8.—Five-day mean sea level charts to correspond with Figure 7. Isobars are drawn for every 5 millibars (except intermediate lines, dashed) and are labeled with last 2 digits only.

For the week ending October 6, temperatures averaged below normal from the Continental Divide to the Atlantic coast, with the exception of central and southern Florida. From Texas through the Ohio Valley temperatures averaged 9° F. or more below normal, and they were as much as 12° F. below normal in Arkansas. The first killing frost of the season occurred during this period in many sections from the Dakotas to New England and brought the growing season to an end as much as three weeks ahead of normal. Temperatures of freezing or below on the 6th in parts of New York and Pennsylvania were the lowest ever reported for so early in the season. Milder weather with above normal temperatures set in over most of the nation after this early cold snap, but subnormal temperatures prevailed once again late in the month. For the week ending November 3 temperatures averaged as much as 12° F. below normal through southern Texas. Much of this unseasonable coolness was related to an extended period of cloudiness and precipitation which kept daytime maximum temperatures as much as 25° to 30° F. below normal, while minimum temperatures were only 10° to 15° F. below normal. In addition 700-mb. heights were below normal, while at the surface northerly winds persisted from a massive slow-moving high pressure area over the Great Plains (Chart IX).

The unseasonable warmth throughout the West was associated with a stronger than normal upper-level ridge with 700-mb. heights as much as 140 ft. above normal (fig. 1). Greatest temperature departures were observed in California and Arizona, with several California cities

TABLE 2.—*Selected California cities reporting record warmth during October 1958.*

City	Mean temperature (° F.)	Anomaly	Years of record
Sacramento	68.5	+4.7	[illegible]
San Francisco (airport)	63.4	+4.0	[illegible]
Burbank	72.1	+7.0	[illegible]
Los Angeles (city office)	74.0	+7.4	[illegible]
Los Angeles (airport)	72.5	+9.1	[illegible]
San Diego	70.9	+5.9	[illegible]

establishing monthly mean temperature records for October. Some of these are listed in table 2. This abnormally warm weather has persisted now for several months in California, particularly along the coast. Although the October warmth appears to be well related to the mean circulation patterns for that month, another contributing factor would appear to be the above normal sea surface temperatures for waters along the coast, a point discussed in some detail in the previous article of this series [1].

Across the nation as a whole the warmest weather occurred during the week ending October 20, with only the extreme Northeast, south Atlantic coast, and Rio Grande Valley experiencing below normal temperatures. Greatest departures, as much as +12° F., were observed throughout the northern Plains and Rockies at a time when the mean upper-level ridge reached its greatest strength. An all-time October heat record for San Diego, Calif. was established with 98° F. on the 17th. At Los Angeles, Calif., a temperature of 104° F. on the 16th equalled their record for October. In addition to these extremes, many daily temperature records, too numerous to mention, were established during this period in cities from the northern Plains to the Pacific coast. Abundant sunshine accompanied the warmth throughout the West with Sacramento, Calif. receiving 99 percent of the possible sunshine for October, the highest in 54 years of record there (Chart VII-B). A sharp cold front moving into the Northwest on the 18th and 19th brought an abrupt end to the unseasonable warmth in that area. The deepening storm system (Chart X) was accompanied by strong winds, with gusts as high as 85 m. p. h. near Glasgow, Mont., and by heavy snows in the Big Horn Mountains of Wyoming and the Black Hills of South Dakota. (See adjoining article by Kibler and Rogers.)

October was an unusually dry month over much of the United States, with a vast area from the Appalachian Mountains to the Pacific coast receiving substantially less than the normal amount of precipitation (Chart III-B). In portions of the central Plains, Rocky Mountain States, and central California, there was no measurable precipitation at all. This was only the second October in the last 68 in which no precipitation fell at Oklahoma City, Okla.; while only one other October (1933) was completely without precipitation at Grand Island, Nebr. Dry weather has persisted throughout parts of the central Plateau since May 1958, only 14 percent of the normal precipitation having fallen at Salt Lake City, Utah during the period May to October, the driest such period since records were started there in 1874. The combination of little precipitation and sunny skies over much of the country produced excellent harvesting weather.

Near to above normal amounts of precipitation were confined mostly to the Atlantic coast, the far Southwest, and portions of the Lakes Region and northwestern border States (Chart III-B). Heaviest amounts fell in Texas with as much as 5 times the normal amount in the extreme south. At Brownsville, 17.12 inches of rain fell, the largest amount that has ever been recorded there for any October during 87 years of record. Corpus Christi, Tex., with 8.43 inches of precipitation, also established a record for the month. Twice the normal amount of precipitation fell along the immediate coast from North Carolina to Connecticut. At Boston, Mass., the total precipitation since the first of the year was the greatest amount for a corresponding period in 87 years of record.

October's precipitation pattern was for the most part quite well related to the monthly mean circulation. A stronger than normal ridge over western North America and a deeper than normal trough near the Atlantic coast (fig. 1) is a flow pattern most frequently associated with a "dry map" for most of the country. This circulation, along with northerly anomalous flow, tends to prevent penetration of moisture into the country, thus inhibiting precipitation. Moderate to heavy amounts of rainfall along the Atlantic coast were directly related to proximity to the mean trough and to storm systems moving northward along the coast (Chart X).

The heavy rains that occurred in the Southwest are more difficult to relate to the monthly mean circulation patterns; however, small variations in flow at lower latitudes are quite often associated with extreme weather anomalies. The most likely explanation seems to be that this precipitation was associated with the trough over Baja California and stronger than normal easterly anomalous flow at the surface (Inset, Chart XI) and 700 mb. (fig. 1). In addition, southeasterly flow from the Gulf of Mexico advected moist tropical airmasses northward, with resultant heavy precipitation as they overran cool polar airmasses. In order to refine this explanation, a composite mean 700-mb. chart was prepared including only those days (16) on which precipitation was general in the Southwest. This chart (not shown) strongly resembled the 700-mb. height and anomaly fields on the monthly chart, with one exception. The composite chart for days with precipitation showed the High located over the central Gulf of Mexico, more in accordance with what one might expect, whereas the high cell on the monthly mean 700-mb. chart (fig. 1) was over southern Texas where record-breaking rains occurred.

Precipitation along the northwestern border was related, for the most part, to trailing fronts from storm centers moving through Canada. These storms, steered by the mean flow at 700 mb. (fig. 1), were also associated with precipitation in the Lakes Region. Note in Chart X the complete absence of migratory cyclones over much of the United States during October. As determined by Klein [7] there are, on the average, three primary cyclone tracks affecting North America during October. Two of these were in evidence, one through Canada, the other off the Atlantic coast. Absence of the third track, from Nevada to the Lakes Region, was strongly related to the northwesterly flow and precipitation deficiency throughout most of the nation.

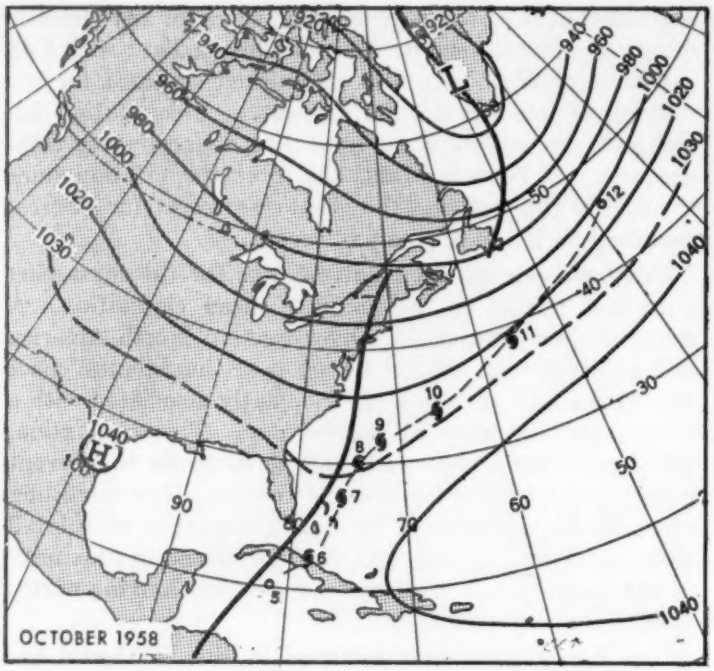

FIGURE 9.—Track of hurricane Janice superimposed upon mean 700-mb. height contours for October (same as fig. 1). Positions shown are for 1200 GMT on dates indicated, while symbols along track define stage of development. Steering of Janice by the mean circulation is well indicated.

FIGURE 10.—Tracks of Pacific typhoons for October 1958 (1200 GMT positions) superimposed upon mean 700-mb. height contours for October 16–30, 1958.

4. TROPICAL STORM ACTIVITY

ATLANTIC

Hurricane Janice was the only tropical storm to develop in the Atlantic during October 1958. This is less than the normal number of such storms given by the 70-year average [8], and represents a continuation of the trend of recent years of less than normal tropical storm activity. Janice's track, superimposed upon the monthly mean 700-mb. contours (same as fig. 1), is shown in figure 9. As reported by Sumner [9]:

Hurricane Janice developed on October 5 as a tropical depression in a strong easterly wave located south of Cuba, which at 1600 GMT was near 20.7° N., 81.7° W. or 175 miles south-southeast of Havana. The depression formed in a large area of heavy squalls and rough seas that had, during the previous three days, drifted westward from the area south of Ciudad Trujillo, Dominican Republic. Ship and commercial aircraft reports from the squally area in the vicinity of Haiti showed winds of 50 m. p. h. but no signs of a circulation. Upon reaching the longitude of western Cuba the depression developed a circulation which moved northeastward across Cuba at a forward speed of about 15 m. p. h. and over the Bahama Islands area some 150 miles to the east of Miami. Late on October 6 the storm developed hurricane intensity. During October 7 and 8 the forward movement slowed to about 7 m. p. h. On the 9th the speed accelerated as the storm moved northeastward over the North Atlantic passing about 300 miles southeast of Cape Race, Newfoundland, on the afternoon of October 11, at which time movement had increased gradually to about 44 m. p. h.

While Janice caused no damage along the southeastern United States coast, some 20 inches of rain in Jamaica resulted in floods which destroyed homes, disrupted communications, and caused severe crop damage. There was also some loss of life in the Bahama Islands and the Greater Antilles.

Janice's track was strongly related to the mean circulation patterns for October. Note how the storm moved northward in the mean trough (fig. 9) until, after it passed 30° N., it was swept rapidly northeastward by fast mid-latitude westerlies. The 15-day mean 700-mb. chart (fig. 3A) shows a similar strong relationship, while the 5-day mean charts (figs. 7A, 8A) show the flow patterns during the early history of Janice's development.

PACIFIC

Three typhoons were observed in the Pacific during October 1958, all during the latter half of the month. This is rather unusual inasmuch as the frequency of these storms normally decreases quite rapidly in October, particularly during the latter half. The tracks of these storms, superimposed on the half-monthly mean 700-mb. map for October 16–30 are shown in figure 10.

Typhoon Kathy was first observed on October 20 as a tropical depression a short distance east of the Philippine Islands. The storm, gradually developing as it moved westward in the subtropical easterly flow, crossed the middle Philippines on the 21st, reaching typhoon intensity early on the 23d in the South China Sea. The forward motion was by then slowed considerably and the storm filled and lost its identity early on the 26th, never reaching the south China coast. The path taken by Kathy followed quite closely the mean trajectory of unrecurved typhoons [7, 10.]

Typhoon Lorna first appeared early on October 23 as a tropical depression a short distance south of Guam. Moving westward in the easterlies, the storm underwent a rather unusual history of development. According to aircraft reconnaissance the storm increased rapidly in intensity to reach full typhoon strength early on the 24th. Within 24 hours however, the storm weakened considerably and was reported as a tropical depression on the 25th.

Gradual intensification occurred thereafter until the storm once again became a full typhoon on the 28th. Slow recurvature followed, and, although strong winds raked the Philippines, Lorna's eye did not penetrate the Islands proper. As the storm sped northward into the westerlies, steered by the mean flow (fig. 10), it followed rather closely the mean trajectory for recurved typhoons [10.]

Typhoon Marie was first observed on October 25 as a tropical depression near 13.5° N., 155.0° E. This storm developed rapidly to typhoon intensity within 24 hours and moved slowly northward until the 30th. From October 30 to November 1 the storm took a westerly path as it was blocked temporarily by a high pressure area to the north. On November 1 Marie recurved and accelerated rapidly northward in response to eastward motion of a short-wave trough in the westerlies.

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ANOMALOUS TEMPERATURES OVER THE ROCKY MOUNTAIN STATES OCTOBER 18–22, 1958

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1. INTRODUCTION

The weather feature discussed in this article is a reversal of the monthly normal temperature pattern that occurred during the period October 18–22, 1958. This brief period of low temperatures over the Rocky Mountain States was emphasized because it closely followed maximum temperatures of 80's and 90's near the Canadian Border. "A high of 97° was reported at Wagner, S. Dak. on the 15th . . . . Los Angeles recorded 104° on the 16th equaling the previous record high there for October" [1]. These abnormally high temperatures were quickly eliminated as a rapidly developing cyclone system brought cold air into the Pacific Northwest on the 18th and 19th.

Otherwise, October 1958 weather was generally uneventful with the Western States somewhat warmer and drier than normal while the eastern areas tended to be slightly cooler than normal. A complete discussion of these general features is given by Andrews [2] elsewhere in this issue.

2. GENERAL DISCUSSION

Figure 1 a and b picture the sea level isobars and the 500-mb. pattern as they existed on October 18. The 500-mb. chart is characteristic of the flow that prevailed for about one week prior to the period of this discussion. There was a pronounced long-wave trough in the vicinity of Ship P (50° N., 145° W.), a ridge over western United States, and a broad long-wave trough over eastern United States. Warm temperatures are generally associated with ridges and cold temperatures with troughs.

On October 17 a surface storm developed near Ship N (30° N., 140° W.) just east of the long-wave trough, deepened very rapidly, and on October 19 reached a minimum pressure of 962 mb. (fig. 2). As this Low moved northward into the Gulf of Alaska a portion of the cold air swept inland over the Pacific Northwest, but the main body of cold air remained well off shore behind the deepening storm. This feature was quite well marked in the thickness field, shown as dashed lines on the surface chart for October 18, figure 1a. Prognoses made by the National Weather Analysis Center (NAWAC) at this time indicated that the deep Low would move northward into the Gulf of Alaska, thence north-northwestward with a break-off coming inland over Canada to develop an Alberta Low.

This forecast demanded that the long-wave trough remain off shore and that only a short-wave trough move inland. Such was not the sequence of events. The surface Low did move into the Gulf of Alaska as forecast, but, instead of only a short-wave trough moving eastward through the Canadian Rockies, the entire long-wave trough moved eastward as developments in the western Pacific disturbed the equilibrium of the westerlies.

The meteorologist is regularly confronted with the problem of whether to forecast eastward progression of the long-wave pattern or to forecast a quasi-stationary long-wave pattern and migratory short waves. There does not seem to be a clear-cut answer for choosing one solution in preference to the other. Frequently, as seems to be pertinent in this situation, the clue should be sought upstream. Consequently, attention is directed to the western Pacific.

Near the tip of Kamchatka in figure 1b can be seen the beginnings of a new major storm system that brought about the change. On the surface chart (fig. 1a) only an east-west trough is visible. As the upper trough (fig. 1b) superimposed its vorticity upon the thermal field of the surface system, rapid cyclogenesis followed [3]. The wave with the 1008-mb. central pressure at 0000 GMT, October 18, became a mature occluded cyclone of 972 mb. near 49° N., 177° W. in 24 hours (fig. 2).

The failure to evaluate properly this spontaneous development directly influenced the prognosis for the west coast area. With such a development in the Pacific, the wavelength became too short to permit the long-wave trough to remain offshore of California. Consequently as the trough pushed eastward to adjust itself, the main body of cold air was forced inland and a rapid drop in temperature followed.

By 0000 GMT, October 19 (fig. 2), the deep mass of cold air had entered Washington and much of Oregon with an apparently insignificant flat wave located just off northern California. As the 500-mb. trough and associated vorticity moved to the California coast, it became superimposed on the "apparently insignificant" wave. Once again there was a sort of spontaneous action. At 0000 GMT, October 19, 12-hr. pressure change charts constructed at NAWAC indicated rising pressures from 120° W. to 155° W. longitude. This picture changed abruptly by 0600 GMT with weak 12-hr. pressure falls along the

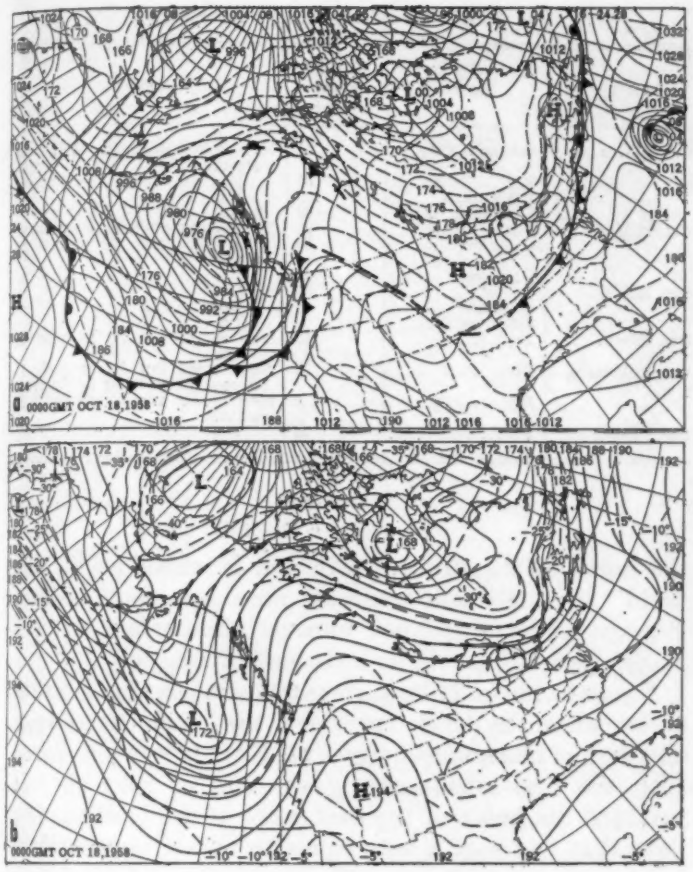

FIGURE 1.—0000 GMT, October 18, 1958. (a) Sea level isobars (solid lines) and 1000–500-mb. thickness contours (dashed lines) in hundreds of geopotential feet. (b) 500-mb. contours (solid) in hundreds of geopotential feet and isotherms (dashed) in °C.

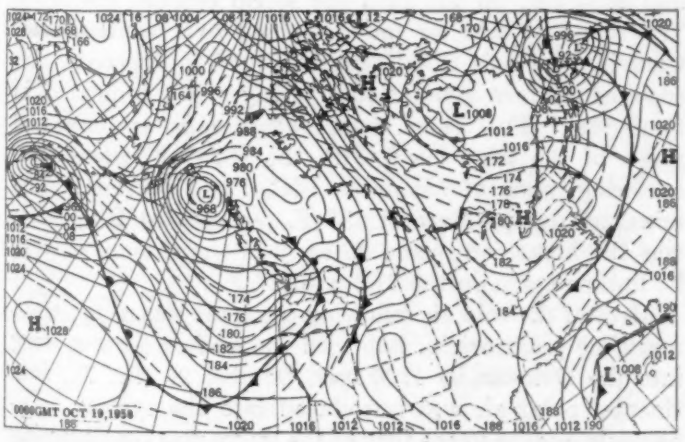

FIGURE 2.—0000 GMT, October 19, 1958. Sea level isobars (solid lines) and 1000–500-mb. thickness contours (dashed lines) in hundreds of geopotential feet.

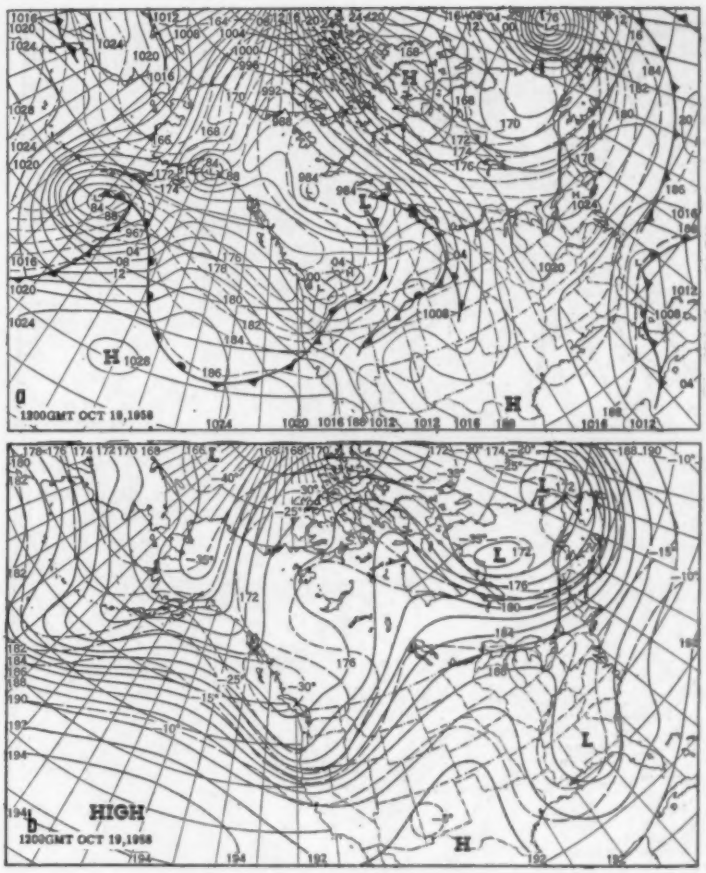

FIGURE 3.—1200 GMT, October 19, 1958. (a) Sea level isobars (solid lines) and 1000–500-mb. thickness contours (dashed lines) in hundreds of geopotential feet. (b) 500-mb. contours (solid) in hundreds of geopotential feet and isotherms (dashed) in °C.

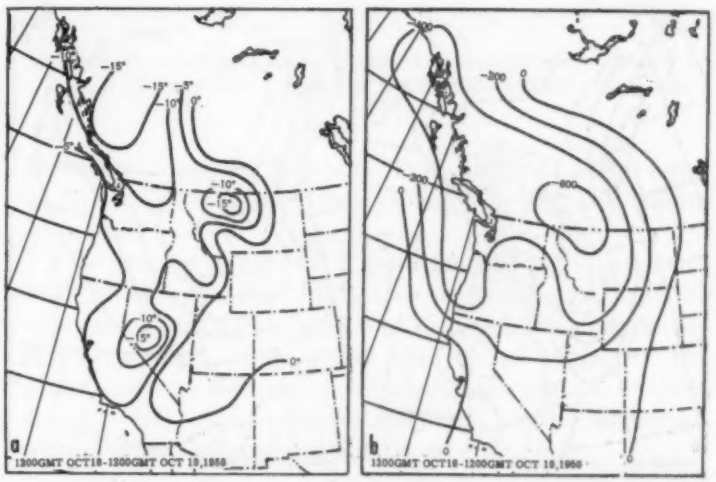

FIGURE 4.—24-hour change for period ending 1200 GMT, October 19, 1958. (a) Surface temperature. (b) 1000–500-mb. thickness.

Oregon-California border and 3-hr. tendencies of −2.5 mb. By 1200 GMT the weak 12-hr. falls had grown to 10-mb. falls and the 3-hr. tendencies to −5.0 mb., followed closely by 5.0-mb. rises. One might be tempted to insert a cold front in such a tendency field.

The surface chart and 1000–500-mb. thickness pattern for 1200 GMT, October 19 (fig. 3a), shows that such a solution is not in keeping with the density concept of fronts. Thickness lines may be considered as lines of equal density or of equal virtual temperature. Hence an examination of the thickness pattern shows a discontinuity of density gradient along the front as analyzed.

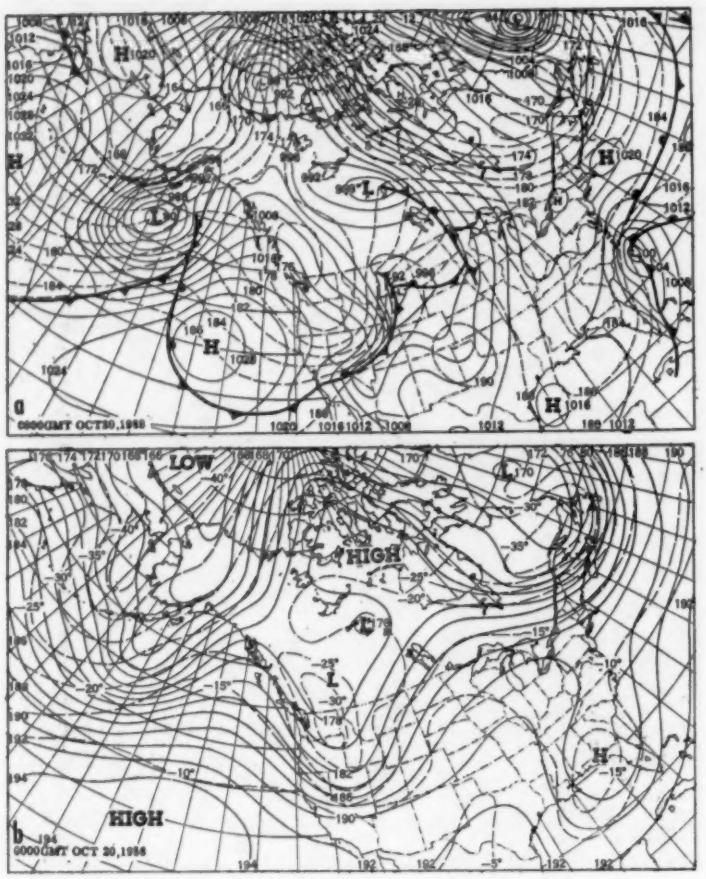

FIGURE 5.—0000 GMT, October 20, 1958. (a) Sea level isobars (solid lines) and 1000–500-mb. thickness contours (dashed lines) in hundreds of geopotential feet. (b) 500-mb. contours (solid) in hundreds of geopotential feet and isotherms (dashed) in °C.

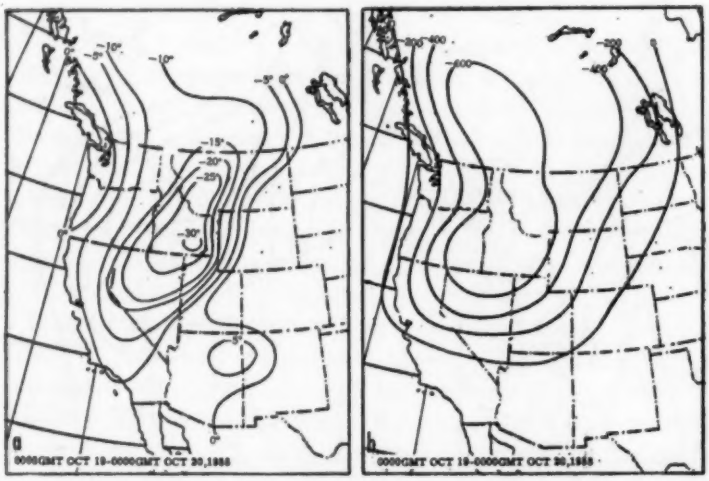

FIGURE 6.—24-hour change for period ending 0000 GMT, October 20, 1958. (a) Surface temperature. (b) 1000–500-mb. thickness.

If one insists on the classic development of an occlusion, this too is an impossible solution. The problem of what to call this sharp line in the tendency field frequently causes misunderstandings among meteorologists. Some meteorologists have attempted to solve the problem with their "trowal." When a surface Low develops well to the north of the surface wave and is embedded in the "cold" air, the classic occlusion process is not followed. Perhaps under these not unusual circumstances, "occlusion genesis" should be a recognized analysis

TABLE 1.—*Record temperature data*

Date/Type	Station	Temperature (° F.)	Record
Oct. 18/Max	Salt Lake City	83	New record high for so late in season.
	Ely	80	Do.
	Los Angeles	100	Do.
	San Diego	98	Do.
Oct. 19/Max	Pueblo	85	Equaled highest for so late in season.
	Great Falls	80	New record high for so late in season.
	Cheyenne	80	Do.
Oct. 20/Max	Pueblo	87	Do.
	Goodland	90	Do.
	Salt Lake City	82	Do.
Oct. 20/Min	Ely	13	New record low for so early in season.
Oct. 21/Min	Elko	8	New record low for so early in season and new low for October.
	Ely	8	New record low for so early in season.
Oct. 22/Max	Ely	53	Do.

Figure 4a shows 24-hr. surface temperature changes that accompanied the development over the Pacific Northwest. The area of maximum change over Nevada was associated with the first small-scale penetration of cold air. It heralded the break of the heat wave of the previous few days that had sent temperatures to record highs so late in the season (table 1). The large area of maximum temperature change over Montana was the result of the deep cold air that moved inland with the long-wave trough.

During the 12 hours between 1200 GMT on the 19th and 0000 GMT on the 20th the storm reached maturity. The dome of cold air moved inland over southwestern Canada with axis tilted southeastward to Nevada. Associated surface temperature changes are indicated in figure 6a. The 24-hr. temperature falls encompassed much of the west coast, with the −20° F. isallotherm enclosing much of Montana, Idaho, and Nevada. The minimum temperature of 13° F. recorded at Ely, Nev., was the lowest on record so early in the season, only to be broken again on the 21st with 8° F.

Most of the cold air following the front was of apparent maritime polar origin, but with the surface Low moving into the Dakotas by 1200 GMT, October 20 (fig. 7a) continental polar air was introduced into the system. Apparently adding to the fury of the storm was the damming effect of the mountains as the easterly surface winds turned southward over Montana. During this period Glasgow recorded peak winds of 85 m. p. h. The effect of blocking in the upper pattern also entered the picture and the surface Low decelerated. From 0000 GMT, October 19 to 1200 GMT, October 20, the Low had moved at 33 kt. During the next 12 hours motion was negligible.

The blocking pattern is clearly seen in figures 5b, 7b, and 11b. In each chart a split in the strong westerly current is evident along the west coast with one portion going northeastward over the ridge in western Canada,

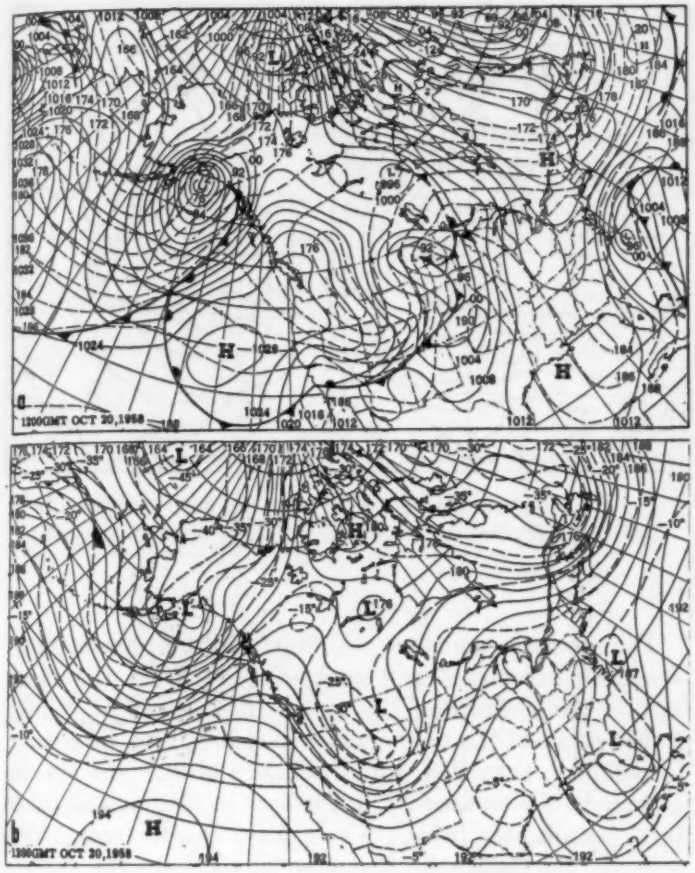

FIGURE 7.—1200 GMT, October 20, 1958. (a) Sea level isobars (solid lines) and 1000–500-mb. thickness contours (dashed lines) in hundreds of geopotential feet. (b) 500-mb. contours (solid) in hundreds of geopotential feet, isotherms (dashed) in °C.

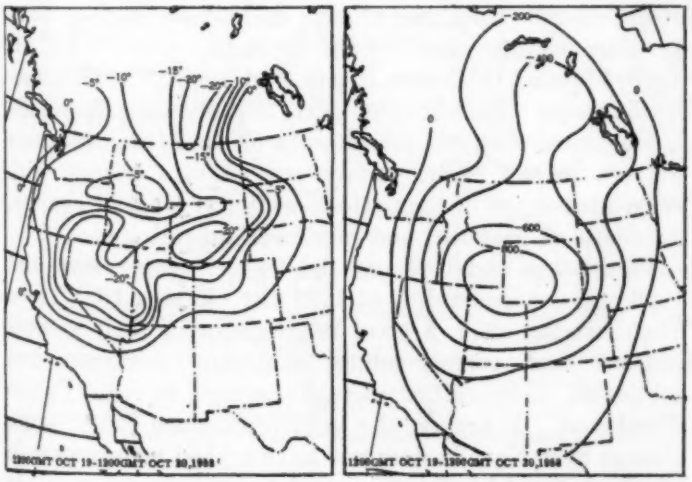

FIGURE 8.—24-hour change for period ending 1200 GMT, October 20, 1958. (a) Surface temperature. (b) 1000–500-mb. thickness.

and the other portion curving sharply eastward and southeastward around the Low over the Rockies.

The sharpness of the temperature change reached a maximum for the 24-hr. period ending at 0000 GMT, October 21 (fig. 10a). Just to the lee of the mountains, where record warm temperatures were experienced on

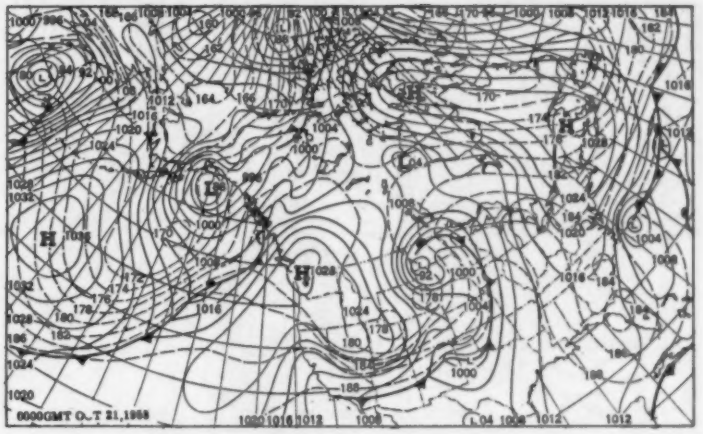

FIGURE 9.—0000 GMT, October 21, 1958. Sea level isobars (solid lines) and 1000–500-mb. thickness contours (dashed lines) in hundreds of geopotential feet.

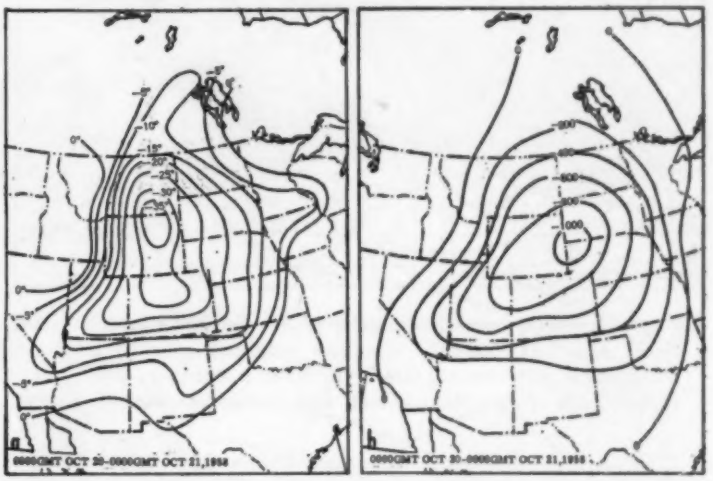

FIGURE 10.—24-hour change for period ending 0000 GMT October 21, 1958. (a) Surface temperature. (b) 1000–500-mb. thickness.

October 19 and 20 (see table 1), a center of 24-hr. temperature drop of 35° was recorded over southeastern Montana.

The passage of air over a given station can be analyzed with a time cross-section such as figure 13. The cold air over Seattle October 19, 20, and 21 is shown clearly as the isotherms drop down under the frontal surface. The slight ridge of warming in the isotherm pattern at 1200 GMT October 19 occurred as the wave moved northeastward well to the south of Seattle, as discussed.

To show more clearly the temperature change through a deep layer we have superimposed on figure 13 the 24-hr. temperature change. It is worthy of note that for every change of temperature in the troposphere there is a change of opposite sign in the stratosphere. Also the level of zero temperature change is found very close to the 250–300-mb. layer.

It appears from this chart and from a similar chart published in 1953 [4] that the temperature in the region 250–300 mb. is affected little by these major storms. A series of charts was prepared to point up the temperature

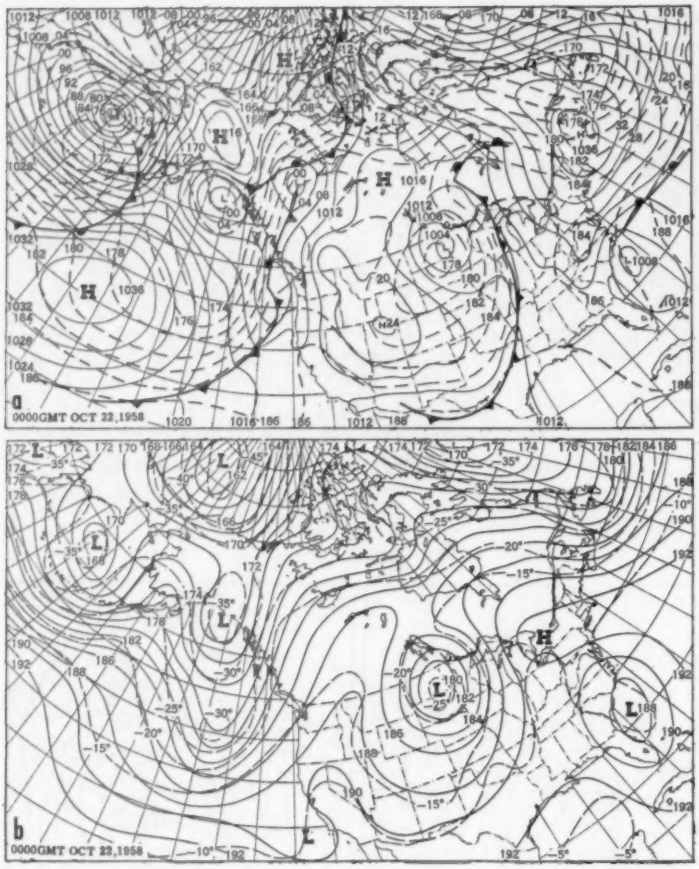

FIGURE 11.—0000 GMT, October 22, 1958. Sea level isobars (solid lines) and 1000–500-mb. thickness contours (dashed lines) in hundreds of geopotential feet. (b) 500-mb. contours (solid lines) in hundreds of geopotential feet, and isotherms (dashed) in °C.

change—thickness change relationship in this situation. A discussion of this relationship follows.

3. SURFACE TEMPERATURE AND THICKNESS CHANGE

The variability of polar air temperature fields when moving is rather well known, and most weathermen are aware of the processes that render surface temperature readings nonrepresentative or nonconservative. For example, a study of trajectories of air and vertical motions over surfaces can be made in a more or less subjective manner, and the results of variations in the stability conditions handled reasonably. However, because the cold outbreak which is presented here moved over the mountains of the Northwest, no attempt has been made to trace trajectories in a detailed manner, but rather to discuss and compare the overall relationships of the 24-hr. changes of the surface temperature and of the 1000–500-mb. thickness. These changes are the basic tools for NAWAC maxima and minima temperature forecasting.

In general, the forecast of degree of change in maximum or minimum temperatures is determined from a relationship between the 1000–500-mb. thickness change and surface temperature change.

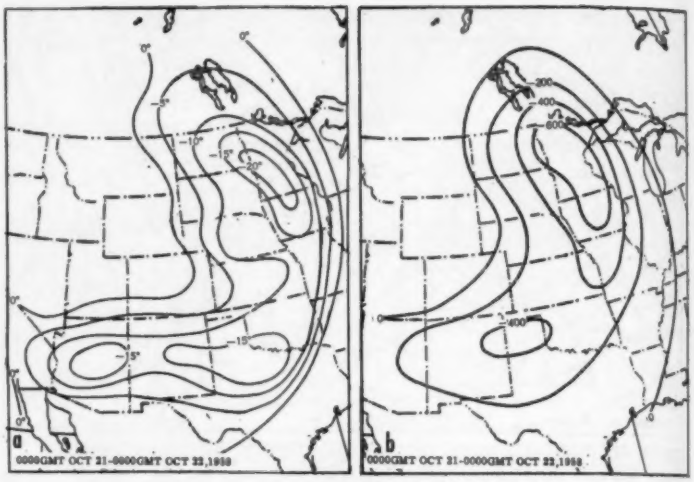

FIGURE 12.—24-hour change for period ending 0000 GMT, October 22, 1958. (a) Surface temperature. (b) 1000–500-mb. thickness.

For example: a change of ±200 ft. in the 1000–500-mb. thickness represents a change of ±5° F. in the mean virtual temperature of this layer. If there is no change in the shape of the temperature sounding, i. e., no change in stability, then this ±5° F. change also represents the change at the surface [5], or for that matter at any other level within this layer. Thus, from the forecast 1000–500-mb. thickness, the first step in reaching the surface temperature change is quantitatively determined. These changes are then adjusted for expected cloud and/or precipitation areas or for other large-scale areas where stability changes may take place.

On the basis of the aforementioned procedures, 24-hr. 1000–500-mb. thickness change and 24-hr. surface temperature change charts were developed from NAWAC 1000–500-mb. thickness charts and regular surface facsimile maps. For the most part, the following discussion is concerned with the relationship of the 24-hr. thickness pattern to the 24-hr. surface temperature change with regard to: shape of the pattern, center of greatest change, gradients of patterns, and numerical magnitudes.

Figure 4 a and b shows the 24-hr. temperature and thickness changes ending at 1200 GMT, October 19. These two patterns show a good relationship in their general pattern and corresponding minimum thickness and minimum temperature change centers in the Pacific Northwest. However, the negative surface temperature change over Nevada does not have a good counterpart in the thickness field. Insufficient data in that area preclude an exact determination of the cause of the lack of agreement, but development of strong surface inversions by radiation is the probable cause.

From figure 6 a and b, it is evident that the polar air had moved over the Pacific Northwest to establish well defined 24-hr. temperature and thickness change patterns. The two patterns closely match. The center of cold air at the surface was in the Pocatello, Idaho area and was elongated north-northeast—south-southwest, whereas the

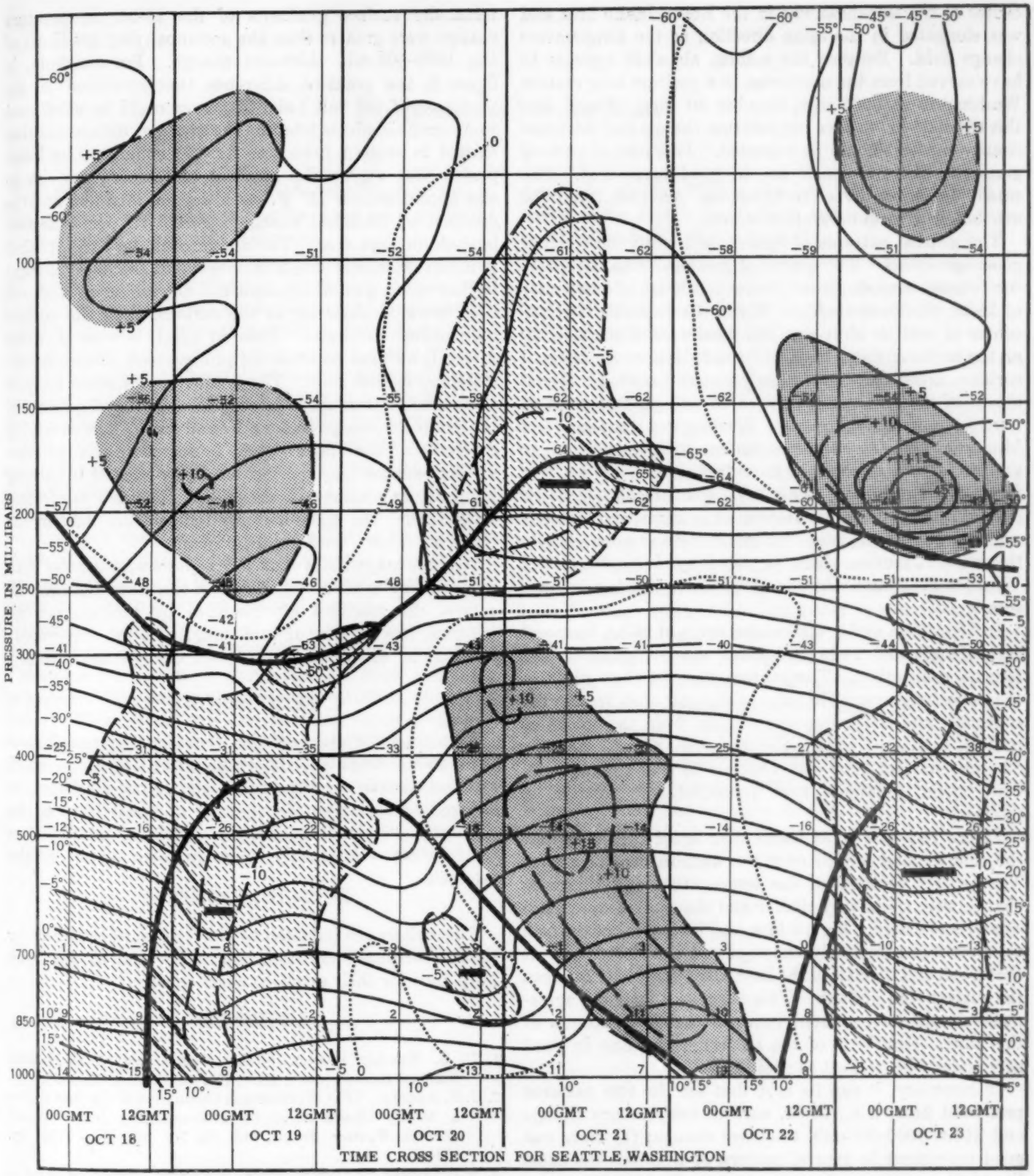

FIGURE 13.—Time cross-section for Seattle, Wash., October 18 to 23, 1958. The plotted temperatures are analyzed by thin solid lines, with fronts and tropopause shown by heavy lines. Dashed lines show 24-hr. temperature change with zero change line dotted.

center of the thickness was in the Boise, Idaho area and was elongated in the same direction as the temperature change field. Because the coldest air aloft appears to have moved from the northwest to a position over eastern Washington at 0000 GMT, October 20 (figs. 3b and 5b), this tilt of 24-hr. surface temperature change and thickness change centers should be expected. Positions of pattern gradients of both charts are in good agreement. The small deviation over northeastern Arizona could be attributed to local orographic effects.

The general patterns of figures 8a and 8b show rather good agreement. The center of greatest 24-hr. temperature change was displaced to the southeast of the center of 24-hr. thickness change. Figure 7b indicates that the center of cold air aloft was still northwest of the cold air at the surface; thus the tilt of the thickness change and surface temperature change centers existed. Visual checks of the gradient in relation to each pattern point to fair agreement except in Washington, Idaho, and Montana. The fact that the surface temperature change pattern lay crosswise of the mountain chain could account for the irregularities. The $-5°$ change (fig. 8a) over northern Idaho could be attributed to increasing stability suggested by the negative vertical motion as portrayed by the vertical motion chart prepared by Joint Numerical Weather Prediction Unit for 1200 GMT, October 20 (not shown).

In figure 10 a and b, the general areas of 24-hr. temperature change and 24-hr. thickness change, more or less bracket each other. The centers were by then tilted in the opposite sense. That the coldest air aloft was to the southeast and southwest was evident from the thickness pattern associated with the surface map (fig. 9), and the 500-mb. map for 0000 GMT, October 21 (not shown here). Once again, gradients were comparable in relation to position.

Figure 12 a and b, 24 hours after figure 10, shows that the cold air had moved over the western central Plains. The general patterns of the temperature and thickness change were again very similar and the centers were more closely associated. Figure 11 a and b shows that the cold air aloft had completely encompassed the closed Low at that level, and the axis of the Low tilted very little between the surface and 500 mb. This suggests that good agreement should have existed between the two patterns at this time. Gradients of the patterns were also in good agreement with respect to position.

In summary, it can be said that for the two patterns presented here, i. e., 24-hr. surface temperature change and 24-hr. 1000–500-mb. thickness change: (1) there was good agreement in general pattern of negative thickness lines and negative surface temperature change; (2) centers were tilted, or out of phase, with the same tilt as the cold dome itself; and (3) gradients of corresponding thickness and temperature change patterns were approximately in the same geometric position in each pattern.

Consideration of magnitudes of the gradients in this series of charts, shows that at the forward edge of the patterns the surface gradients of the 24-hr. temperature change were greater than the accompanying gradients of the 1000–500-mb. thickness change. For example, in figure 6, the gradient difference that stretched to the southeast of the Salt Lake City area could be attributed to orographic effects whereas the gradient differences that existed in eastern Iowa (see fig. 12) could not be interpreted that way. The gradient of temperature change was approximately 15° F. per 2 degrees latitude, and the gradient of thickness change was 400 ft. per 2 degrees latitude in that area. The above could be accomplished (within restrictions of $\pm 5°$ F. $= \pm 200$ ft. thickness change) by the mean virtual temperature decreasing at a slower rate, toward colder air at the surface, than the surface temperature decreased. This, in effect, is what occurred in the Iowa area because the process took place through a sloping frontal zone. The gradients of surface temperature change were more intense because they represented the complete change across a frontal zone. The overlying gradients of the mean virtual temperature change were weaker because they represented an average of the strong temperature gradients in the cold air (beneath the frontal surface) and the quasi-uniform temperature field in the warm air (above the frontal surface).

Also the magnitudes of surface centers were greater than indicated by $\pm 5°$ F. $= \pm 200$ ft. in thickness change. Of course, the relations are modified by temperature inversions, loss or gain of moisture, insolation, orographic effects, and other causes that can change the stability.

4. CONCLUSION

Because the system off the west coast deepened more than was anticipated, the temperature forecasts, which are tied directly to the surface and upper air forecasts, suffered accordingly. Recognition of the differences encountered in the 1000–500-mb. thickness and surface temperature relationship may produce more precise forecasts.

ACKNOWLEDGMENTS

The writers are indebted to NAWAC staff members for their constructive criticism and review and to the Daily Map Unit for their excellent chart work.

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2. J. F. Andrews, "The Weather and Circulation of October 1958—A Month Characterized by a Pronounced Index Cycle," *Monthly Weather Review*, vol. 86, No. 10, Oct. 1958, pp. 408–415.
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4. C. L. Kibler and E. F. Robinson, "Cyclogenesis Aloft Over Southwestern United States, October 17–22, 1953," *Monthly Weather Review*, vol. 81, No. 10, Oct. 1953, pp. 342–347.
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Articles are accepted for the *Monthly Weather Review* with the understanding that they have not been published or accepted for publication elsewhere.

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Tables should be typed, each on a separate page, with a title provided. They should be numbered consecutively in arabic numerals.

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References should be listed on a separate sheet and numbered in the order in which they occur in the text; or, if there are more than 10, in alphabetical order according to author. The listing should include author, title, and source. If the source is a magazine, the volume, number, month, year, and complete page numbers should be listed; if the source is a book, the publisher, place and date of publication, and the page numbers of the reference. If reference is made to a self-contained publication, the author, title, publisher, place and date of publication should be given. Within the text, references should be indicated by arabic numbers to correspond to the numbered list and enclosed in brackets.

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Illustrations. A list of legends for the illustrations should be typed (double spaced) on a separate sheet. Each illustration should be numbered in the margin or on the back outside the image area. To fit into the *Review* page, illustrations must take a reduction not to exceed 3½″ x 9″ (column size) or 7½″ x 9″ (page size). Map bases should show only political and continental boundaries and latitude and longitude lines, unless data are to be plotted, when station circles are also needed. Usually the less unnecessary detail in the background the better will be the result from the standpoint of clear reproduction. Line drawings and graphs should also be uncluttered with fine background grids unless the graph demands very close reading. It is not necessary to submit finished drawings to the *Review*, as drafting work can be done at the time the paper is prepared for publication.

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Description of Charts

CHART I. *A. Average Temperature (° F.) at Surface. B. Departure of Average Temperature from Normal.*—The average monthly temperature presented in Chart I–A is computed from the average daily maximum and the average daily minimum which in turn are computed from the daily maximum and minimum temperatures reported by some 225 first-order Weather Bureau stations and 700 cooperative stations. The departures from normal are presented in Chart I–B. They are based on the 30-year normals (1921–50) for the first-order Weather Bureau stations and on means of 25 years or more (mostly 1931–55) for the cooperative stations.

CHART II. *Total Precipitation.*—

CHART III. *A. Departure of Precipitation from Normal (inches). B. Percentage of Normal Precipitation.*—Chart II is based on daily precipitation records at about 800 weather Bureau and cooperative stations. In Chart III the anomaly in the month's precipitation is shown as a departure from the normal total and as a percentage of the normal total. These anomalies show the deviations from the 30-year normals (1921–50) for about 225 first-order Weather Bureau stations in Charts III A and B, supplemented in Chart III-A by the deviation from means of 25 years or more (mostly 1931–55) for about 700 cooperative stations.

CHART IV. *Total Snowfall.*—

CHART V. *A. Percentage of Normal Snowfall. B. Depth of Snow on Ground.*—Chart IV gives the total depth in inches of unmelted snowfall as reported during the month by Weather Bureau and cooperative stations. This is converted in Chart V–A into a percentage of the normal total amount computed for each Weather Bureau station having at least 10 years of record. The depth of snow on ground is that reported by both Weather Bureau and cooperative stations as of 7:00 a. m. EST on the last Monday of the month. This is reported only for the months December through April. The snowfall charts are presented each month November through April.

CHART VI. *A. Percentage of Sky Cover Between Sunrise and Sunset. B. Percentage of Normal Sky Cover Between Sunrise and Sunset.*—These charts are based on visual observations made hourly at Weather Bureau stations and averaged for the month. Sky cover includes, in addition to cloudiness, obscuration of the sky by fog, smoke, etc. Normal amount of sky cover is computed for stations having at least 10 years of record.

CHART VII. *A. Percentage of Possible Sunshine. B. Percentage of Normal Sunshine.*—Chart VII–A shows the amount of sunshine received in terms of percentage of the total hours of sunshine possible during the month. In Chart VII–B this is shown as a percentage of the normal number of hours of sunshine received. Normals are computed for Weather Bureau stations having at least 10 years of record.

CHART VIII. *Average Daily Values of Solar Radiation, Direct and Diffuse.*—Plotted on the chart are the monthly means of daily total solar radiation, both direct and diffuse, in langleys (gm. cal. $cm.^{-2}$) for all Weather Bureau stations which record this element. Supplementary data, for which limits of accuracy are wider than for those data shown, are drawn upon in making the analysis. The inset shows the percentages of the mean based on the period 1951–55.

CHART IX. *Tracks of Centers of Anticyclones at Sea Level.*—

CHART X. *Tracks of Centers of Cyclones at Sea Level.*—Centers which can be identified for 24 hours or more are tracked in these charts. Semi-permanent features such as the Great Basin and Pacific Highs and Colorado and Mexico Lows are not shown. The 7:00 a. m. EST positions are shown by open circles, with the intermediate positions at 6-hour intervals shown by solid dots. The date is given above the circle and the central pressure to whole millibars below. A dashed track indicates a regeneration rather than actual movement to the next position. Solid squares indicate position of stationary center for period shown beside them.

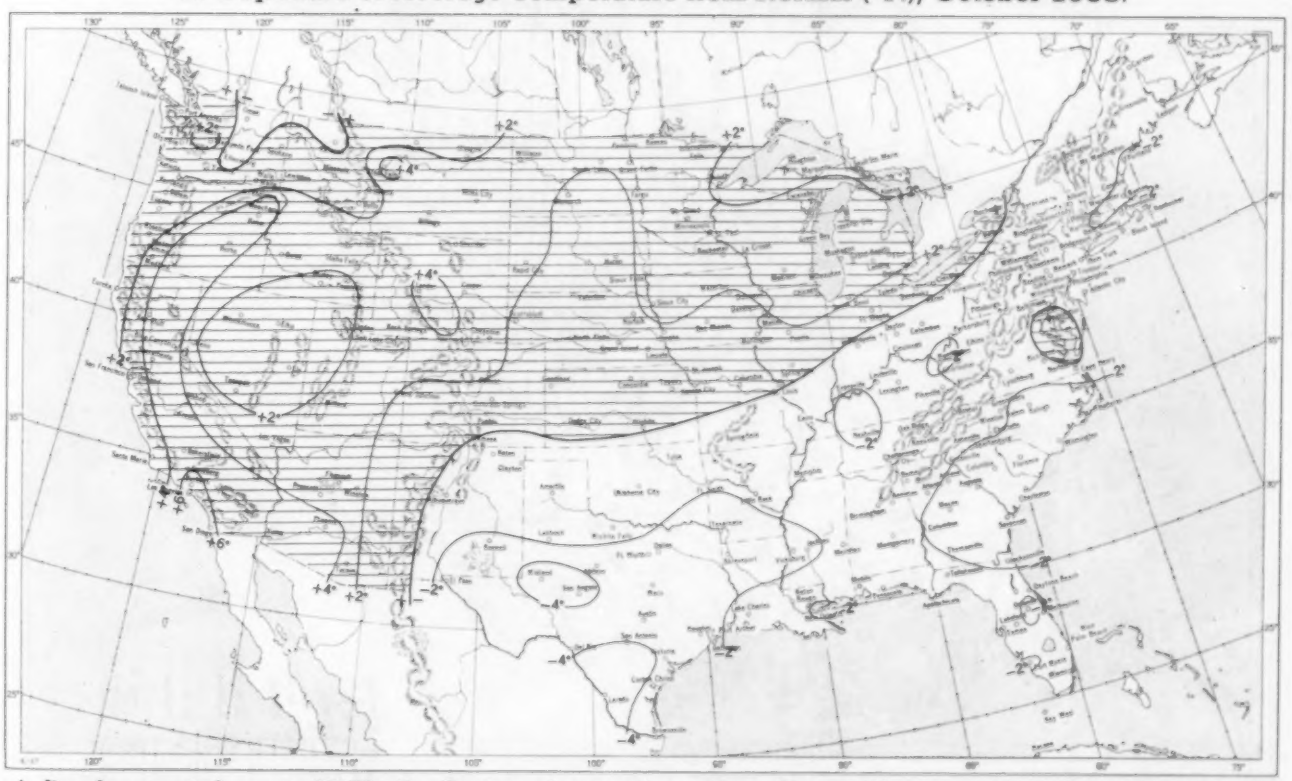
CHART XI. *Average Sea Level Pressure (mb.) and Surface Windroses.*—The average monthly sea level pressure is obtained from the averages of the 7:00 a. m. and 7:00 p. m. EST pressures reported at Weather Bureau stations. Windroses are based on the hourly wind directions (to 16 points of the compass) reported by Weather Bureau stations, each circle or arc indicating 5 percent of the time. The inset shows the departure of the average pressure from the normal average computed for each station having at least 10 years record and for each 10° intersection in a diamond grid over the oceans from interpolated values read from the Historical Weather Maps for the 20 years of best coverage prior to 1940.

CHARTS XII–XVII. *Average Height, Temperature, and Resultant Winds, 850, 700, 500, 300, 200, and 100 mb.*—Height is given in geopotential meters and temperature in degrees Celsius. These are the averages of the 1200 GMT radiosonde reports. Wind speeds are given in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. Directions are shown to 360° of the compass. Winds are based on rawins at 1200 GMT.

NOTE. Tabulations of exact values of most of these charted elements for Weather Bureau stations are printed each month in *Climatological Data—National Summary*, and annual averages are presented in the Annual Issue of that publication each year.

Chart I. A. Average Temperature (°F.) at Surface, October 1958.

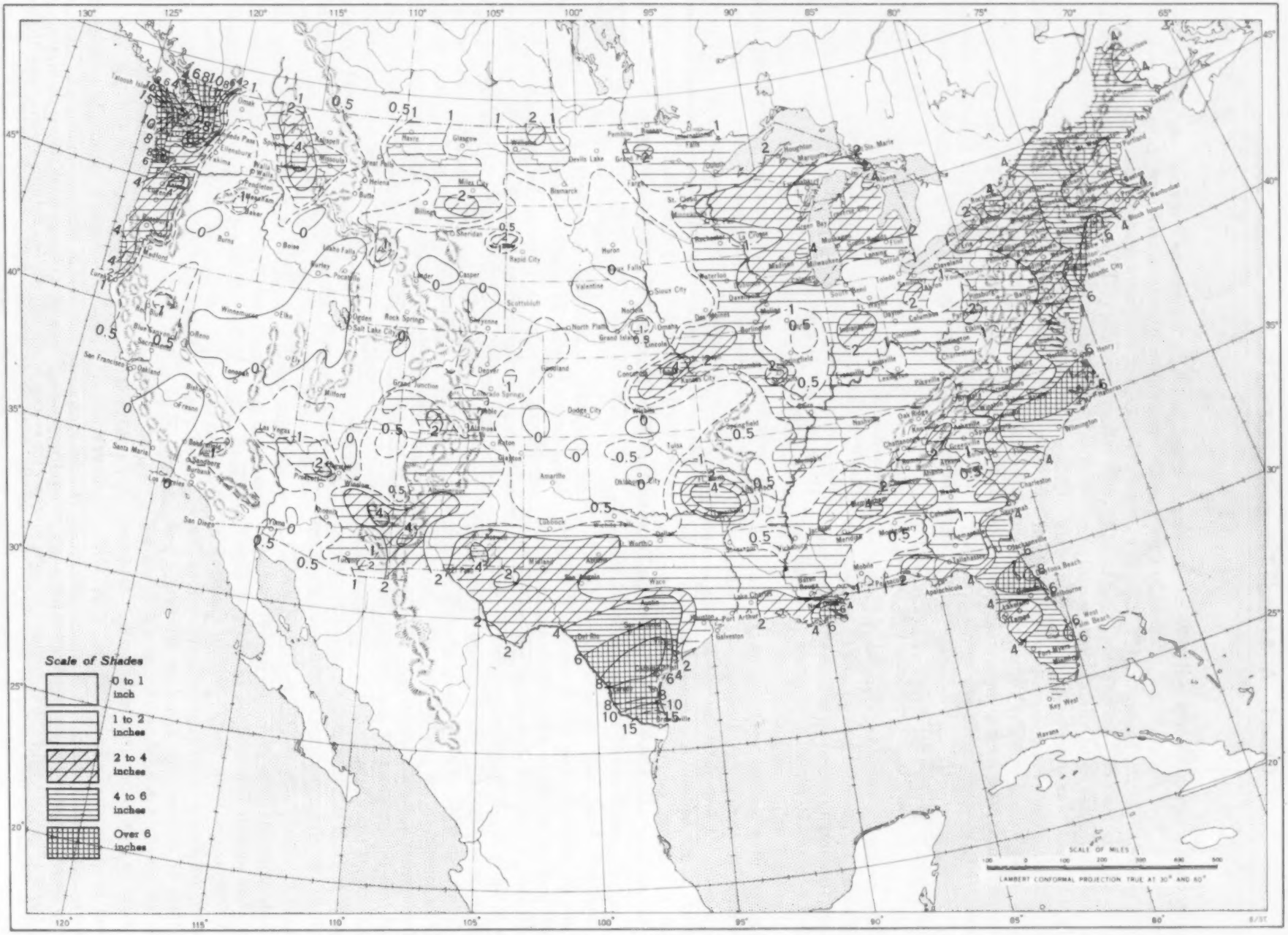
B. Departure of Average Temperature from Normal (°F.), October 1958.



A. Based on reports from over 900 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.

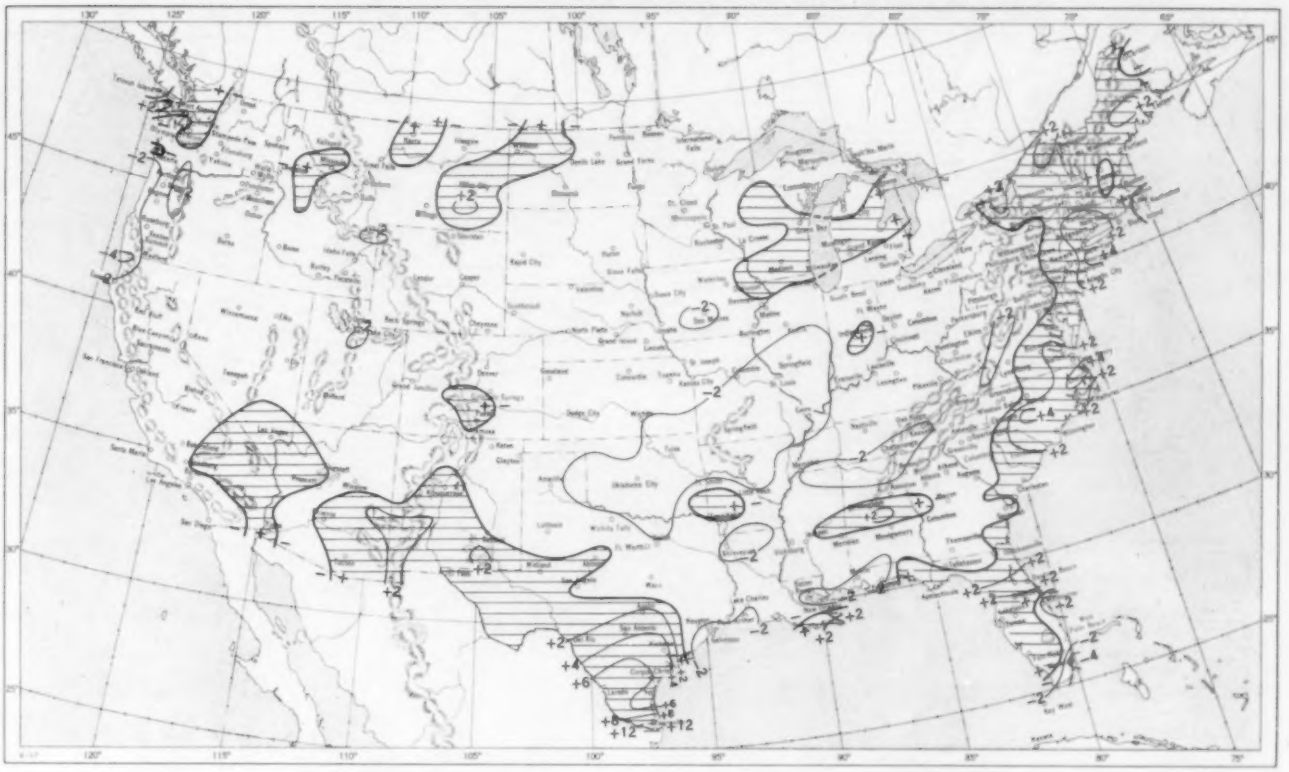
B. Departures from normal are based on the 30-yr. normals (1921-50) for Weather Bureau stations and on means of 25 years or more (mostly 1931-55) for cooperative stations.

Chart II. Total Precipitation (Inches), October 1958.

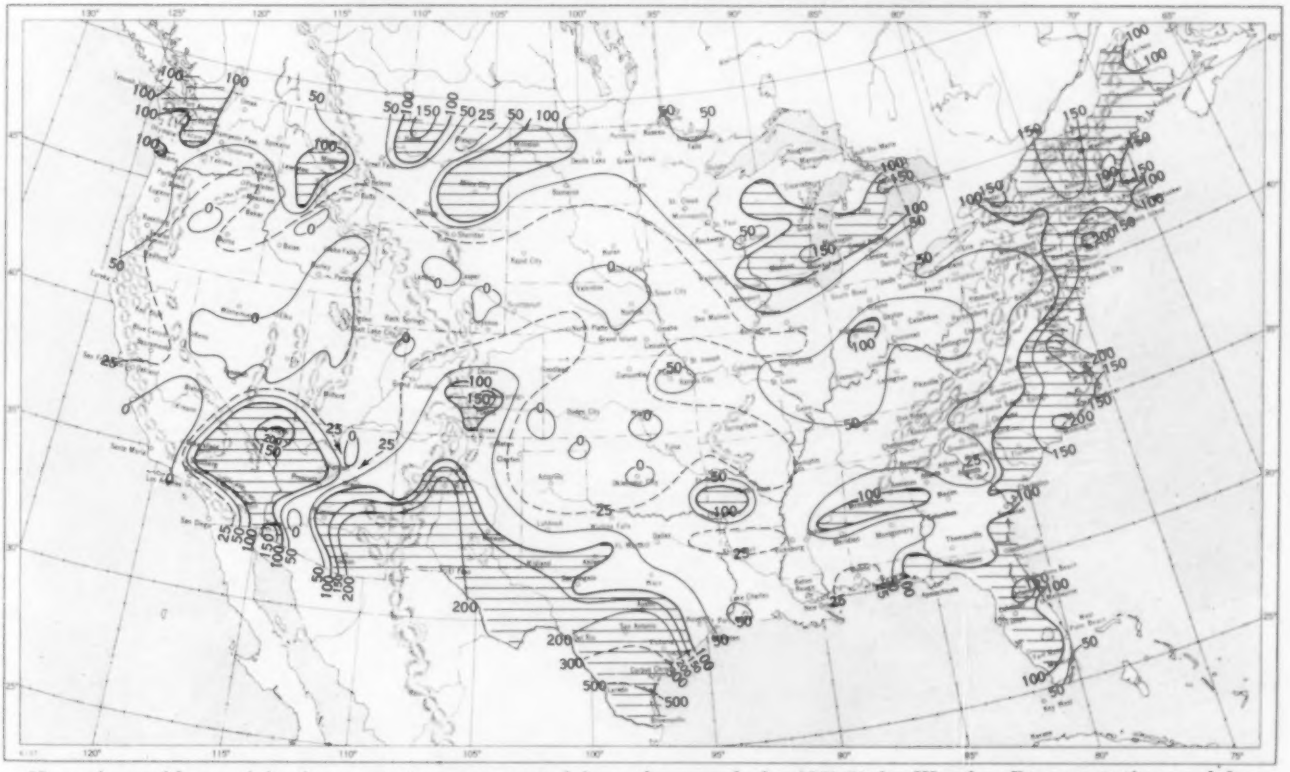

Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Based on daily precipitation records at about 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), October 1958.

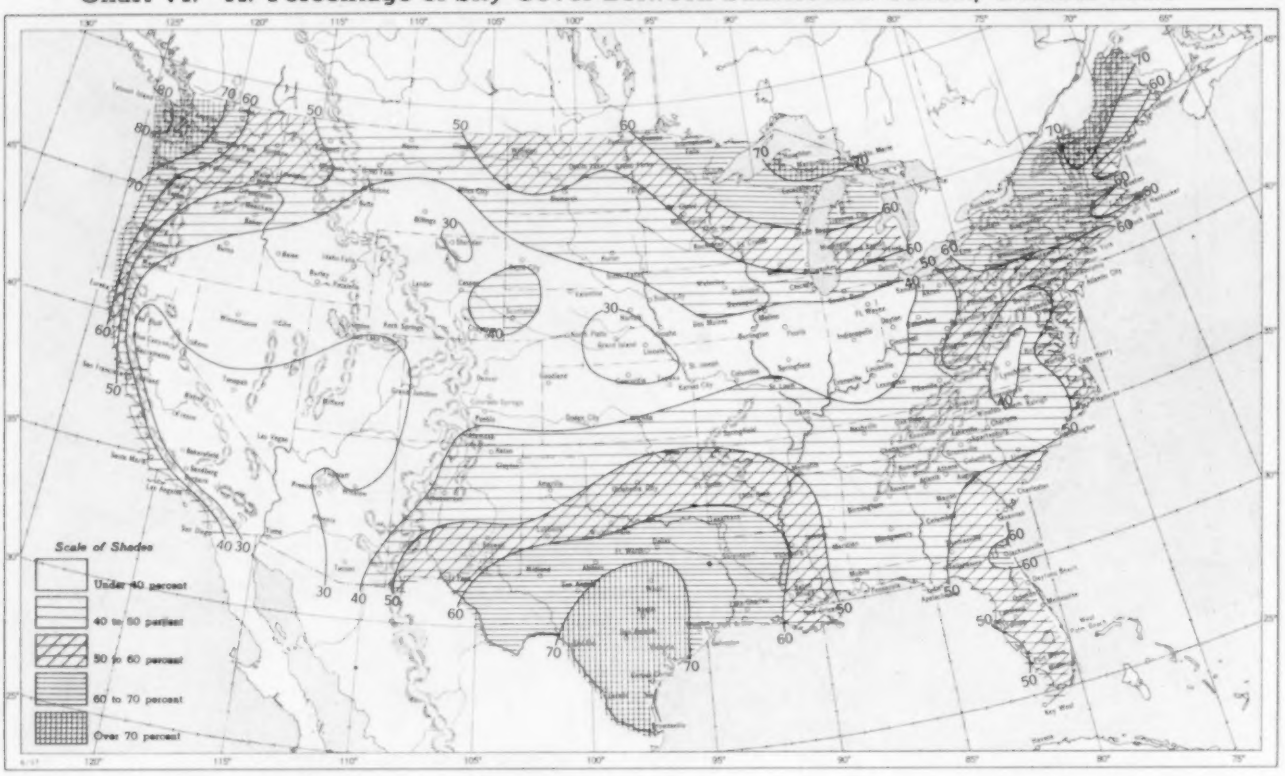


B. Percentage of Normal Precipitation, October 1958.

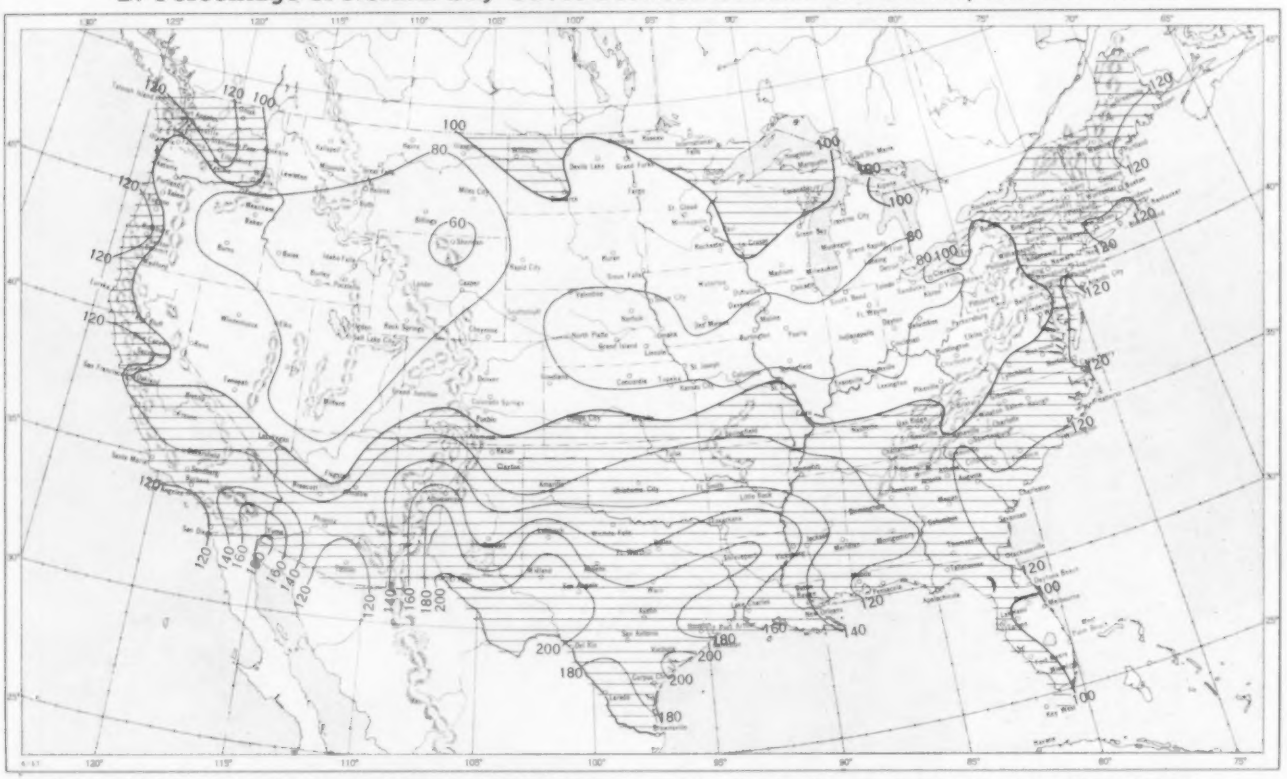


Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, October 1958

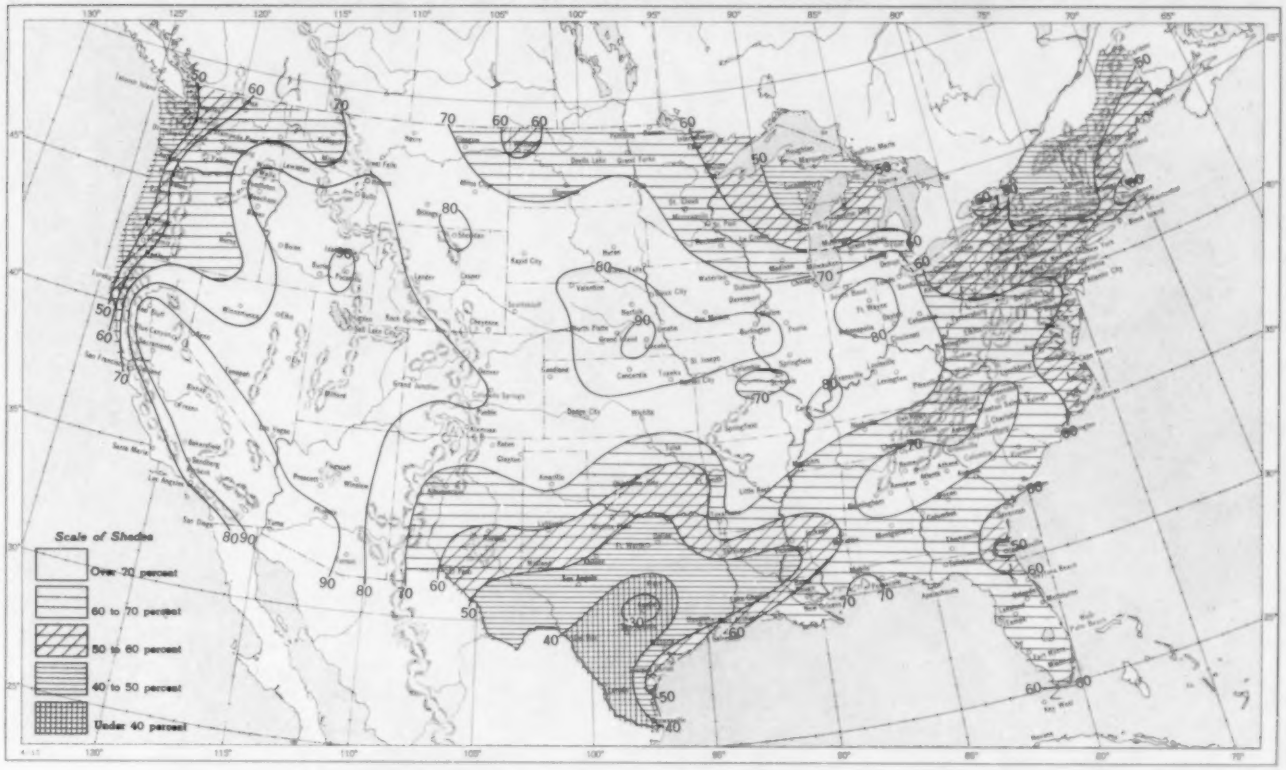


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, October 1958.

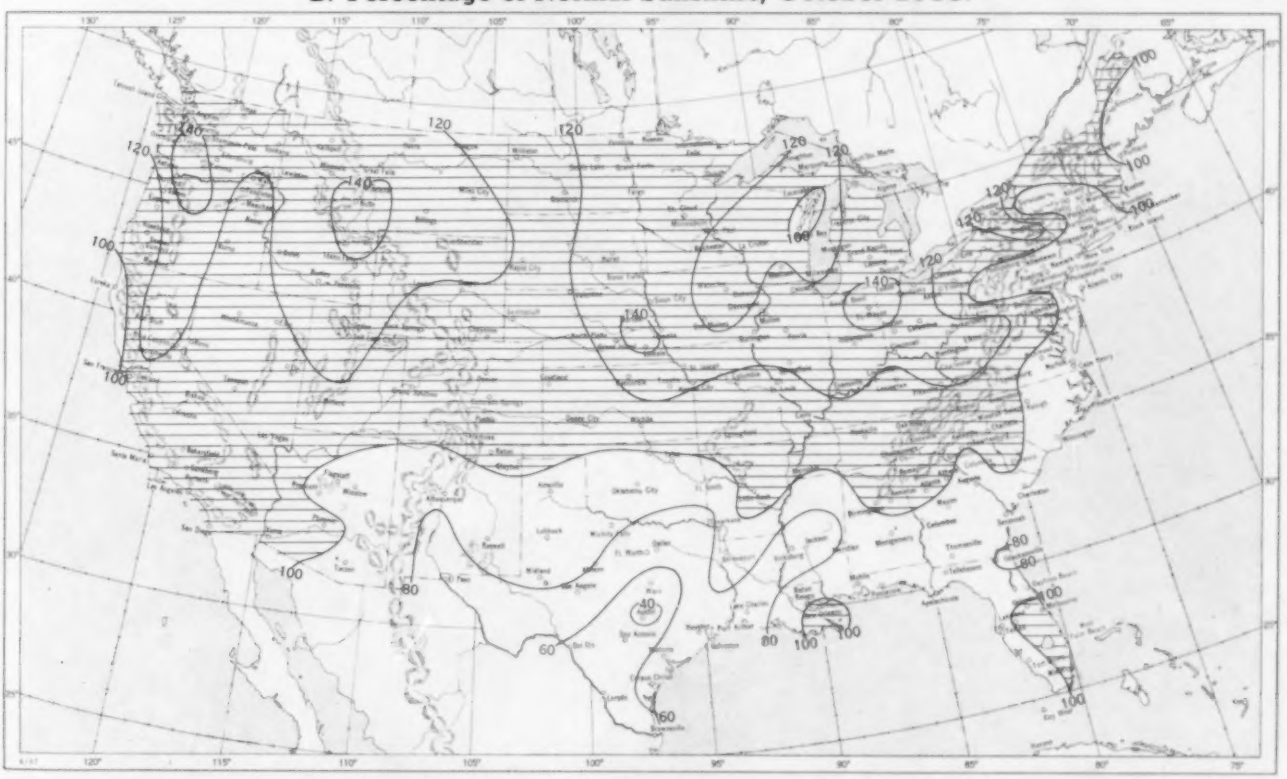


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, October 1958.



B. Percentage of Normal Sunshine, October 1958.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, October 1958. Inset: Percentage of Mean Daily Solar Radiation, October 1958. (Mean based on period 1951-55.)

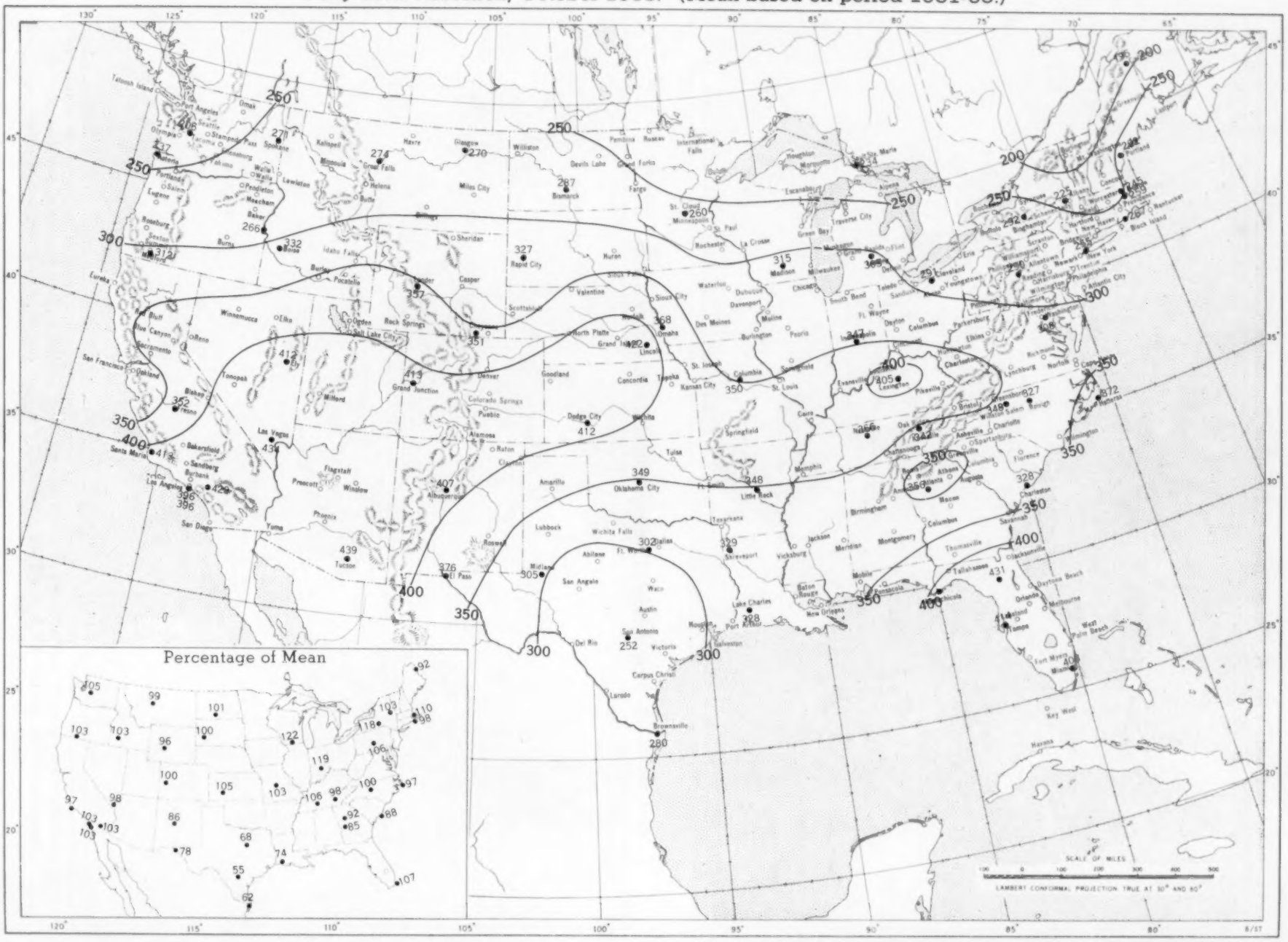
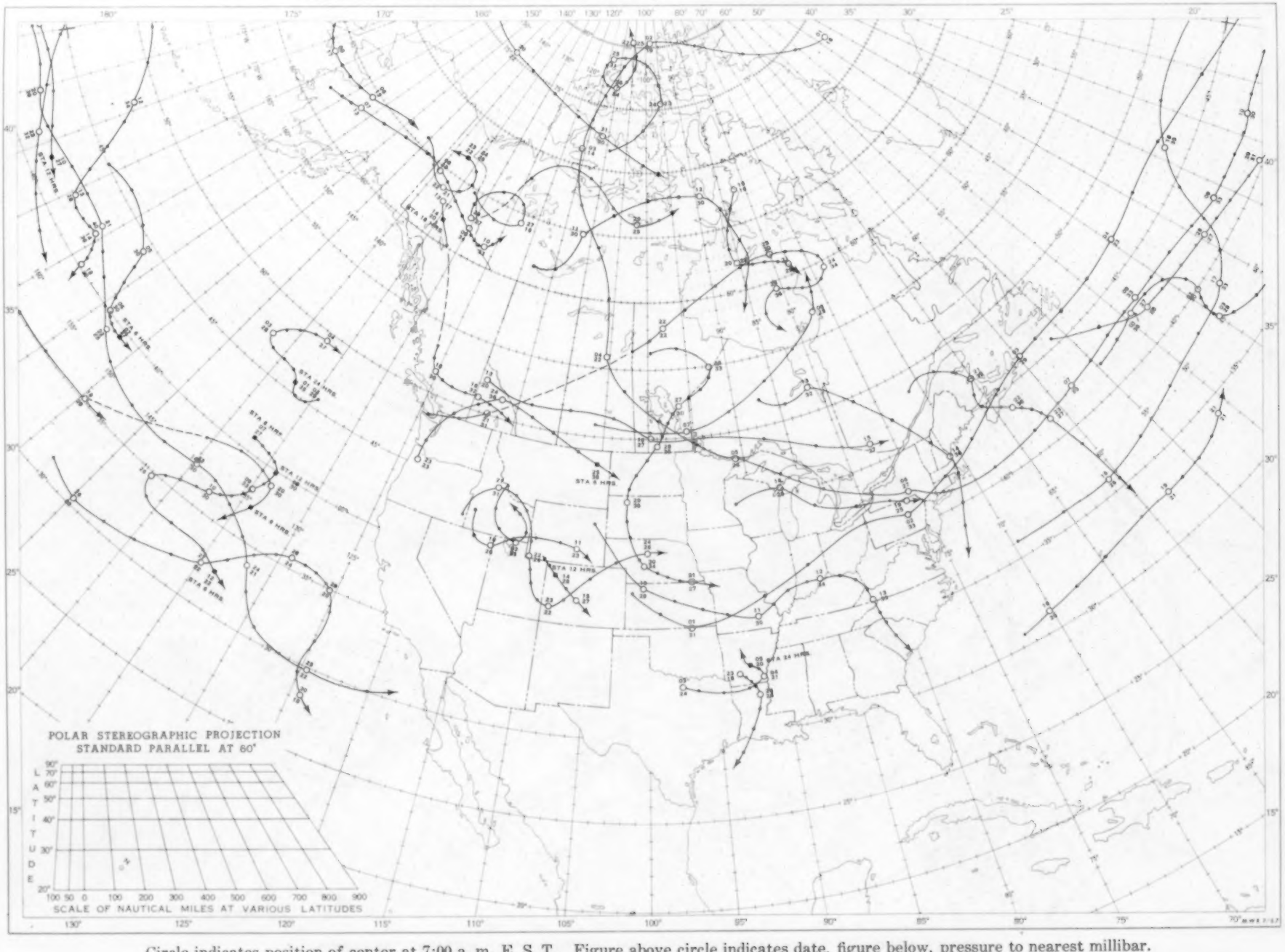


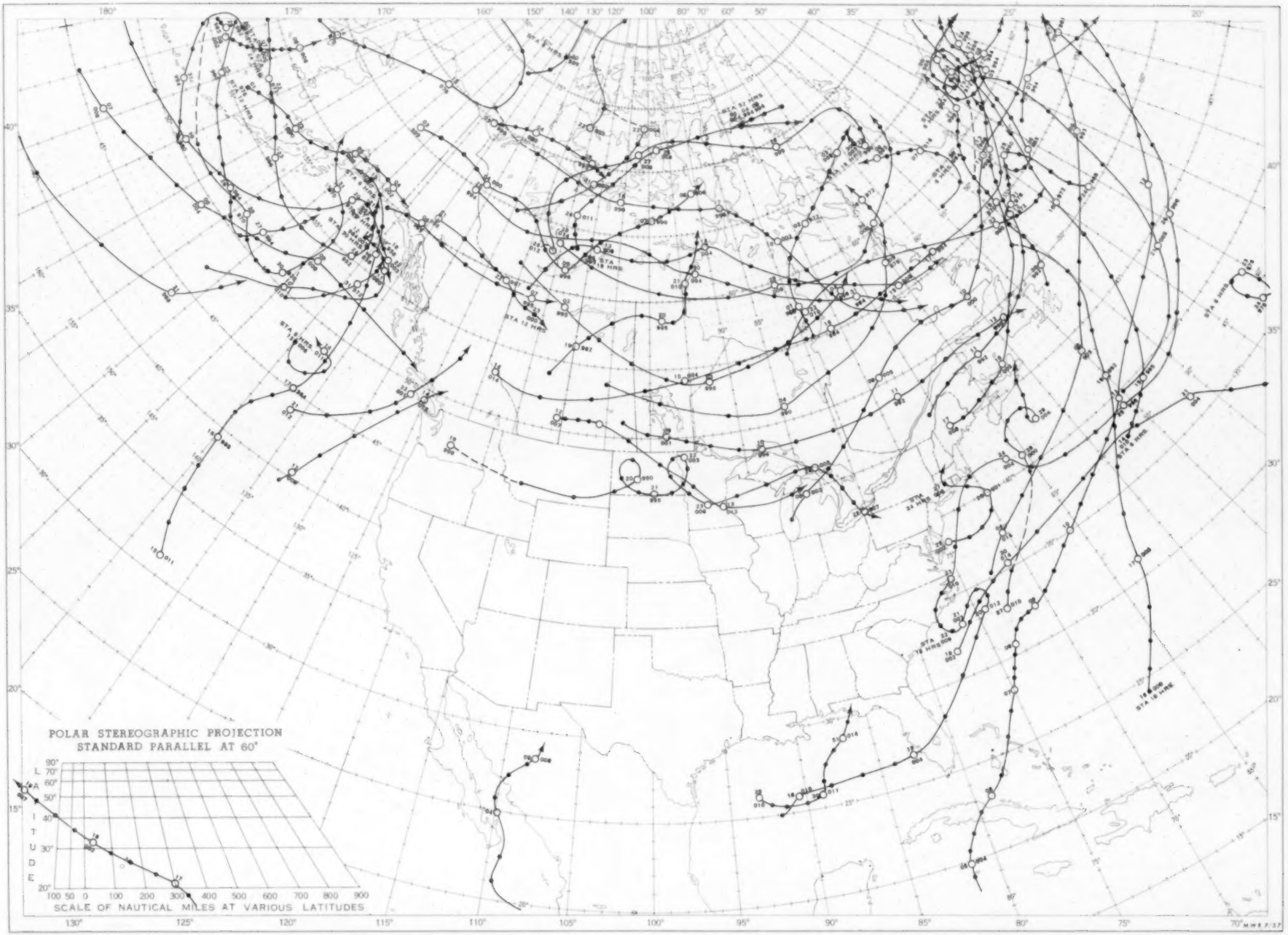
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. The inset shows the percentage of the mean based on the period 1951-55.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, October 1958.



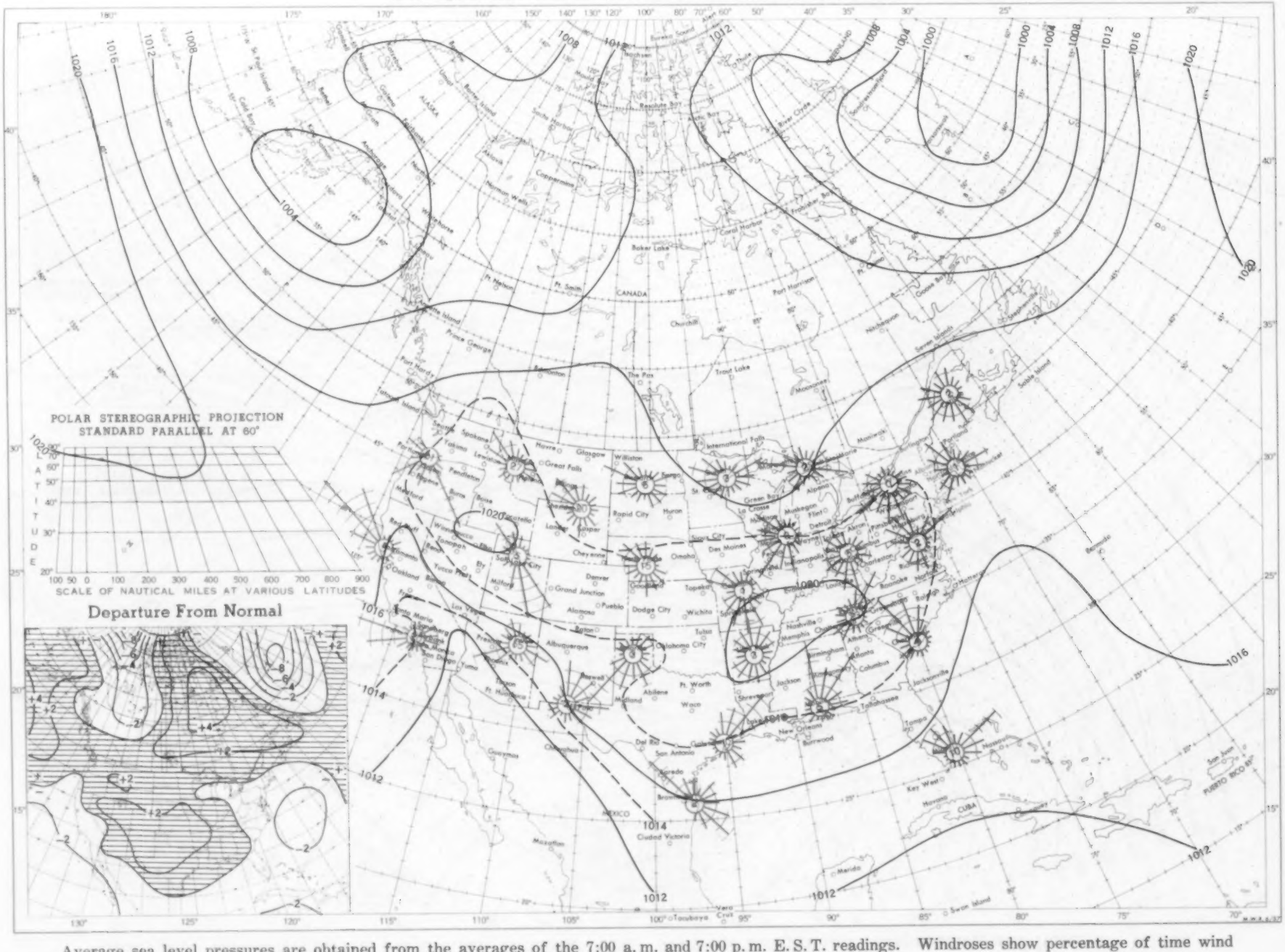
Circle indicates position of center at 7:00 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, October 1958.


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
LATITUDE
90° 70° 60° 50° 40° 30° 20°
100 50 0 100 200 300 400 500 600 700 800 900
SCALE OF NAUTICAL MILES AT VARIOUS LATITUDES

Circle indicates position of center at 7:00 a. m. E. S. T. See Chart IX for explanation of symbols.

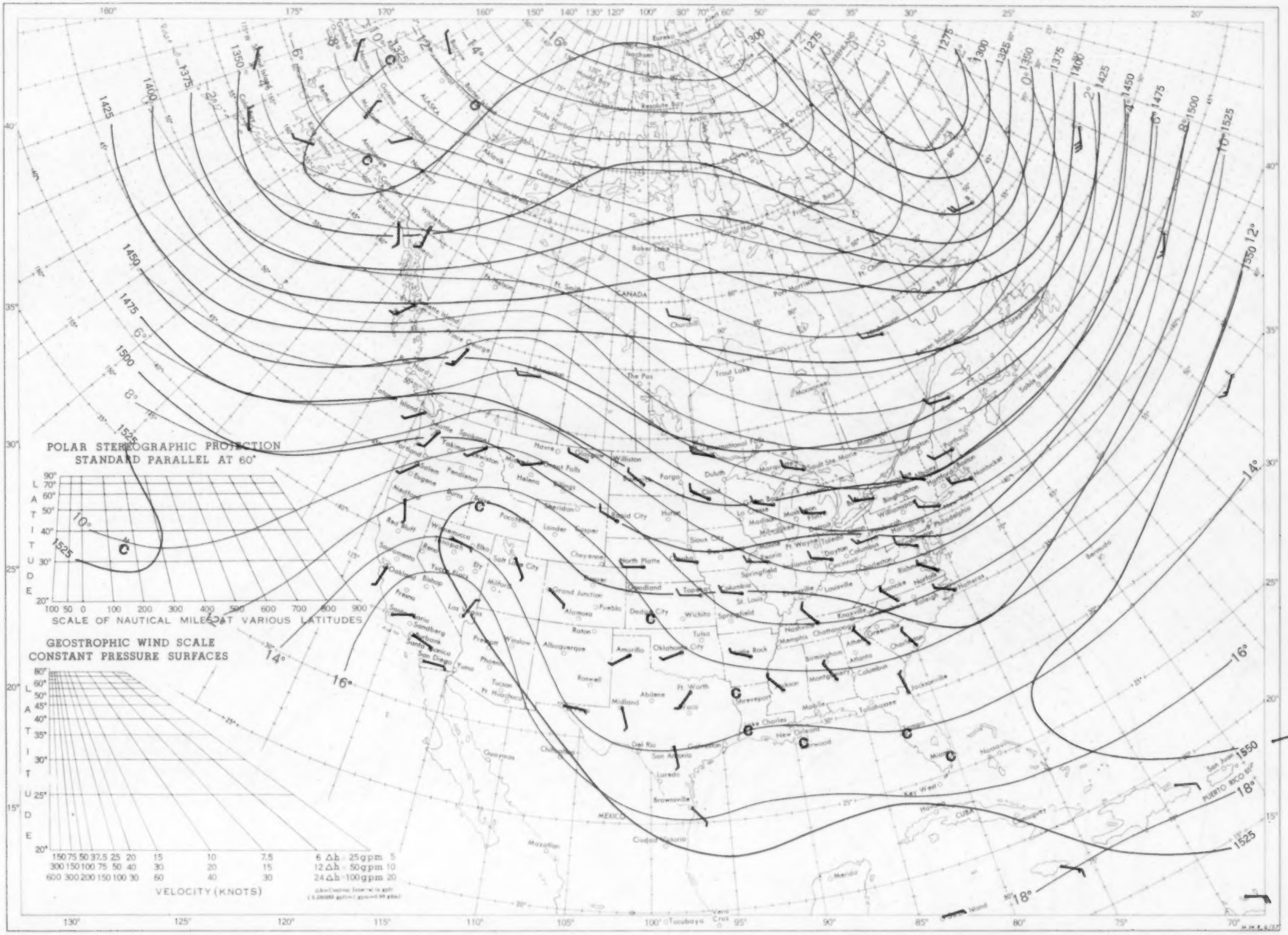
Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, October 1958. Inset: Departure of Average Pressure (mb.) from Normal, October 1958.



OCTOBER 1958

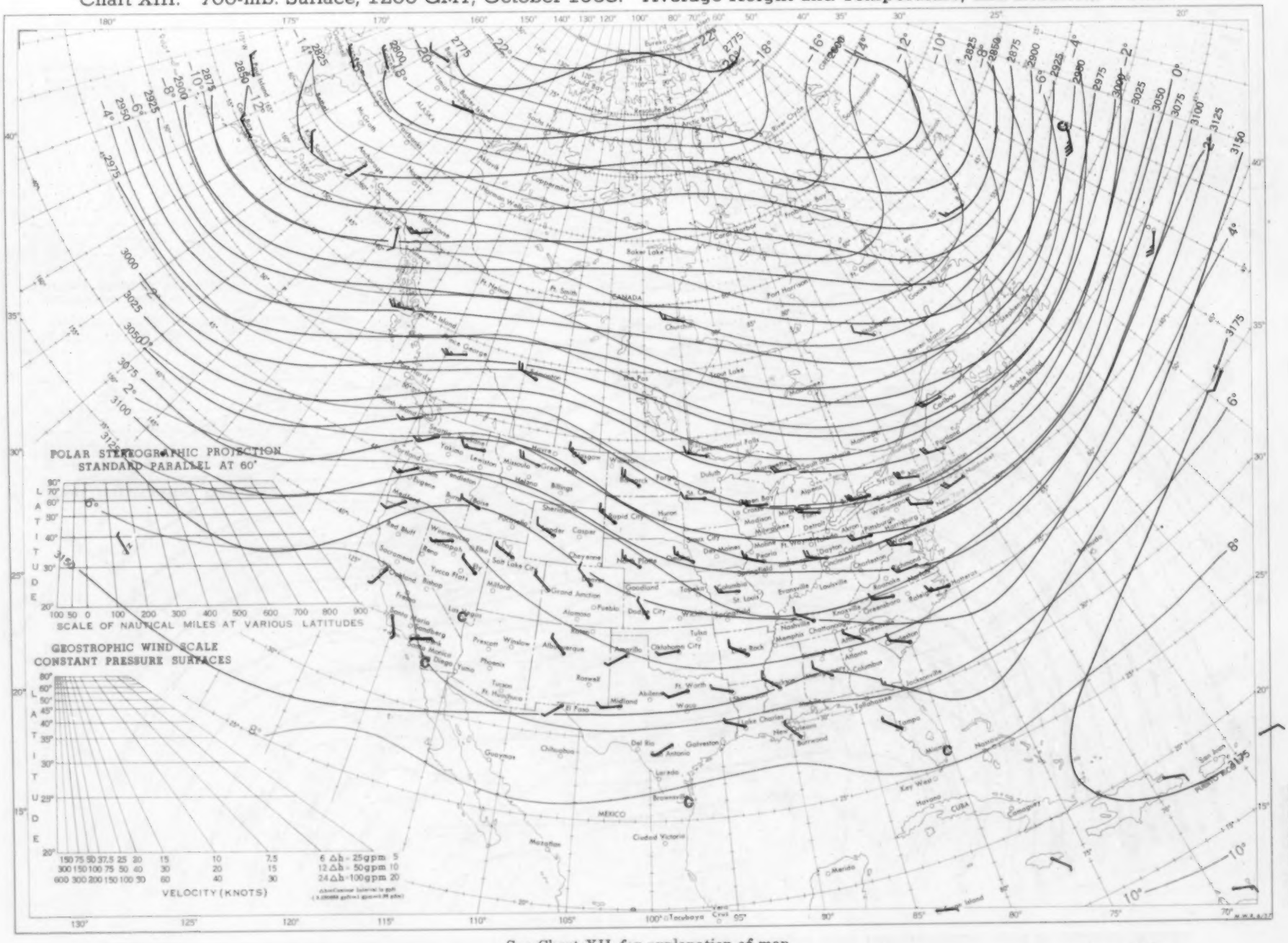
Average sea level pressures are obtained from the averages of the 7:00 a. m. and 7:00 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. 850-mb. Surface, 1200 GMT, October 1958. Average Height and Temperature, and Resultant Winds.



Height in geopotential meters (1 g.p.m. = 0.98 dynamic meters). Temperature in °C. Wind speed in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. All wind data are based on rawin observations.

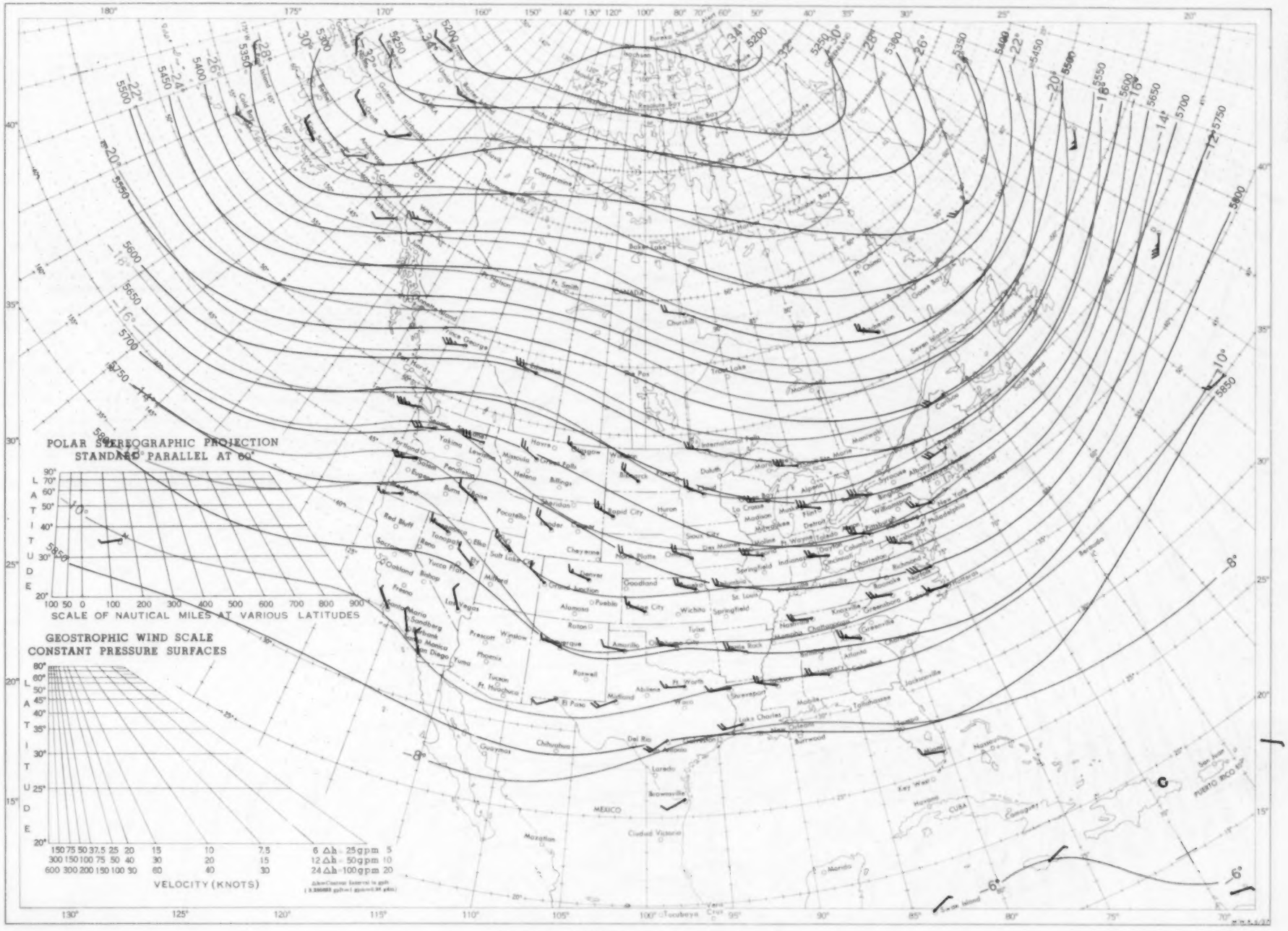
Chart XIII. 700-mb. Surface, 1200 GMT, October 1958. Average Height and Temperature, and Resultant Winds.



OCTOBER 1958

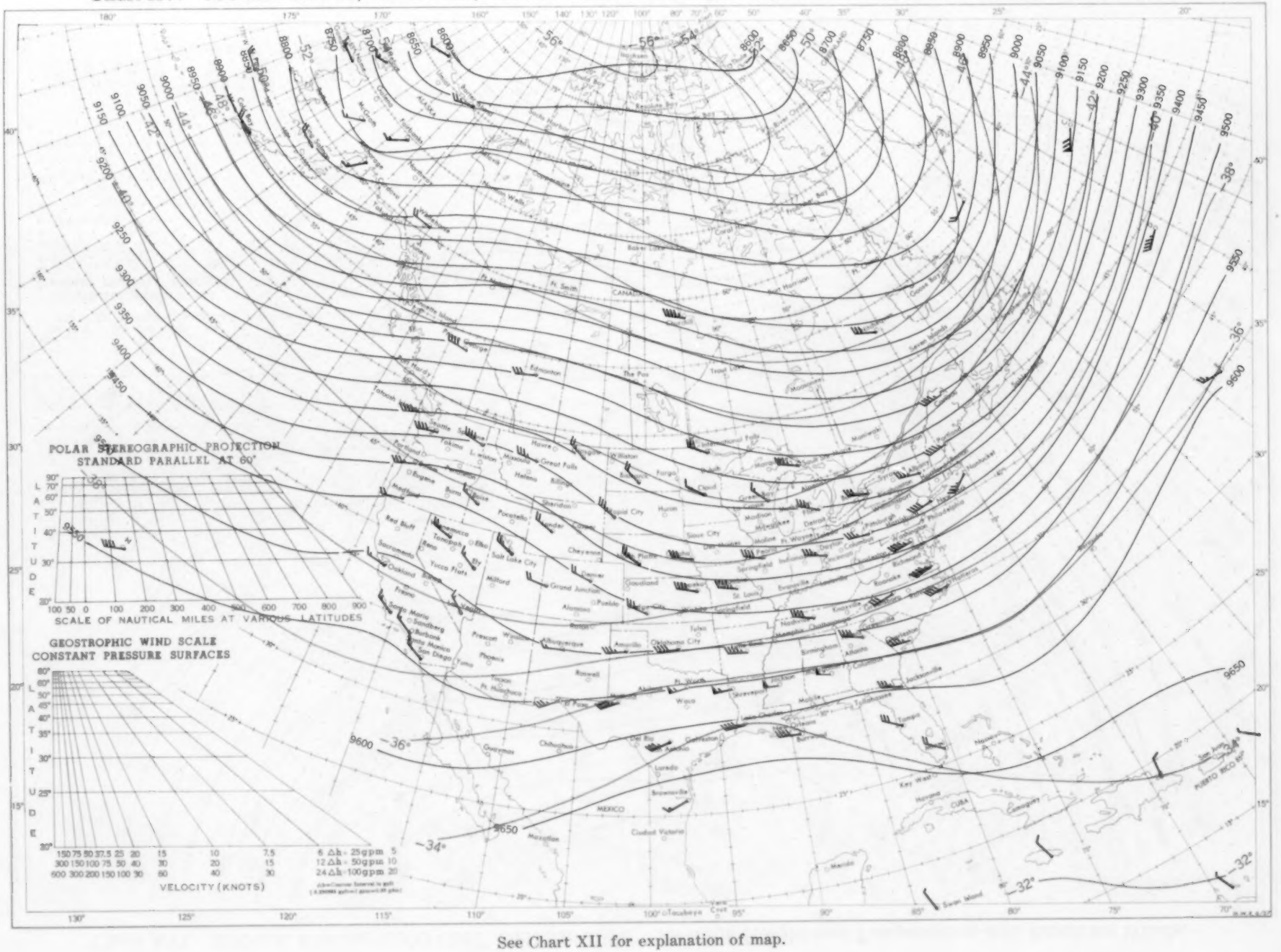
See Chart XII for explanation of map.

Chart XIV. 500-mb. Surface, 1200 GMT, October 1958. Average Height and Temperature, and Resultant Winds.


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
LATITUDE
SCALE OF NAUTICAL MILES AT VARIOUS LATITUDES
GEOSTROPHIC WIND SCALE
CONSTANT PRESSURE SURFACES
VELOCITY (KNOTS)
6 Δh = 25 gpm 5
12 Δh = 50 gpm 10
24 Δh = 100 gpm 20

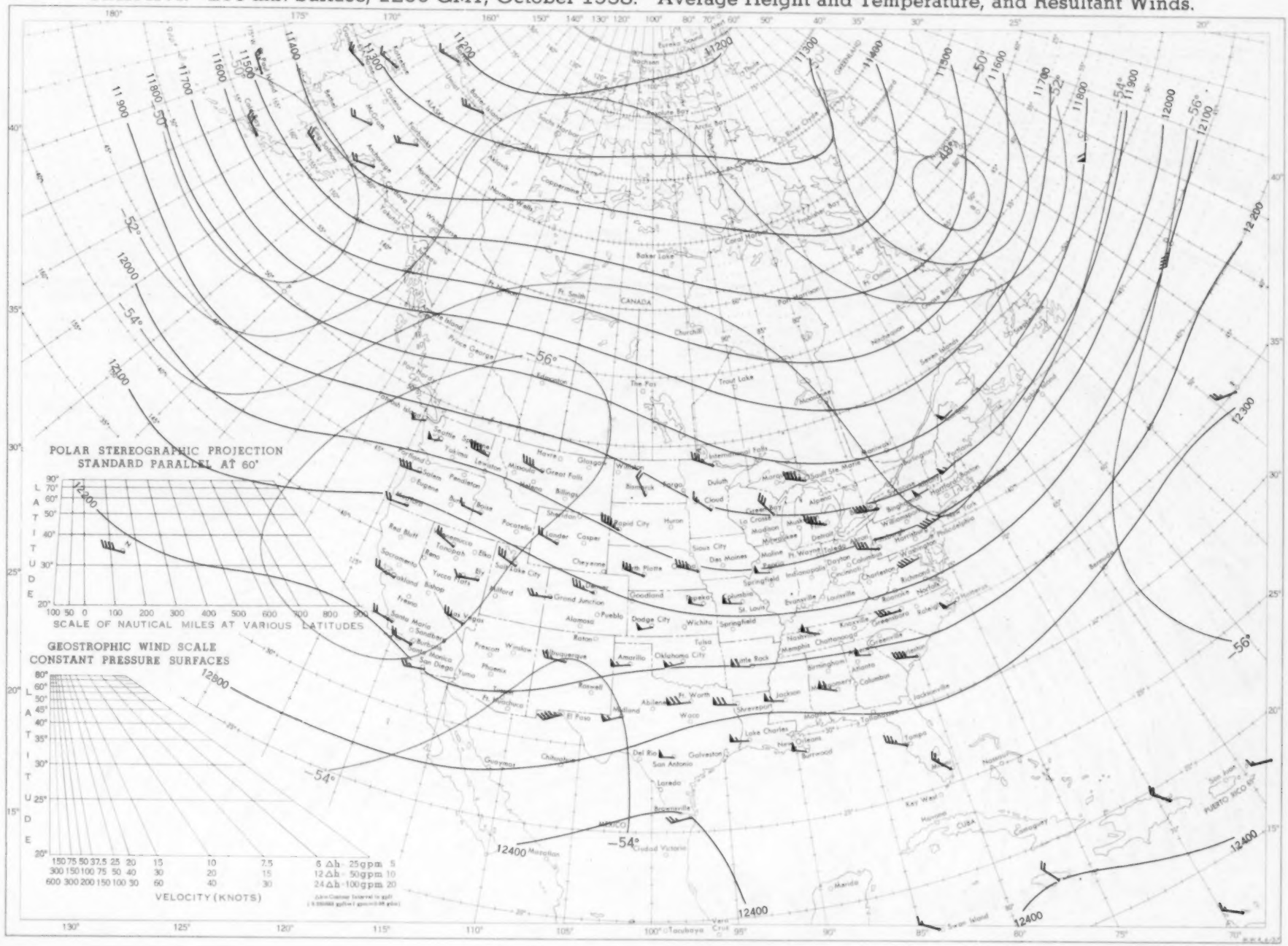
See Chart XII for explanation of map.

Chart XV. 300-mb. Surface, 1200 GMT, October 1958. Average Height and Temperature, and Resultant Winds.



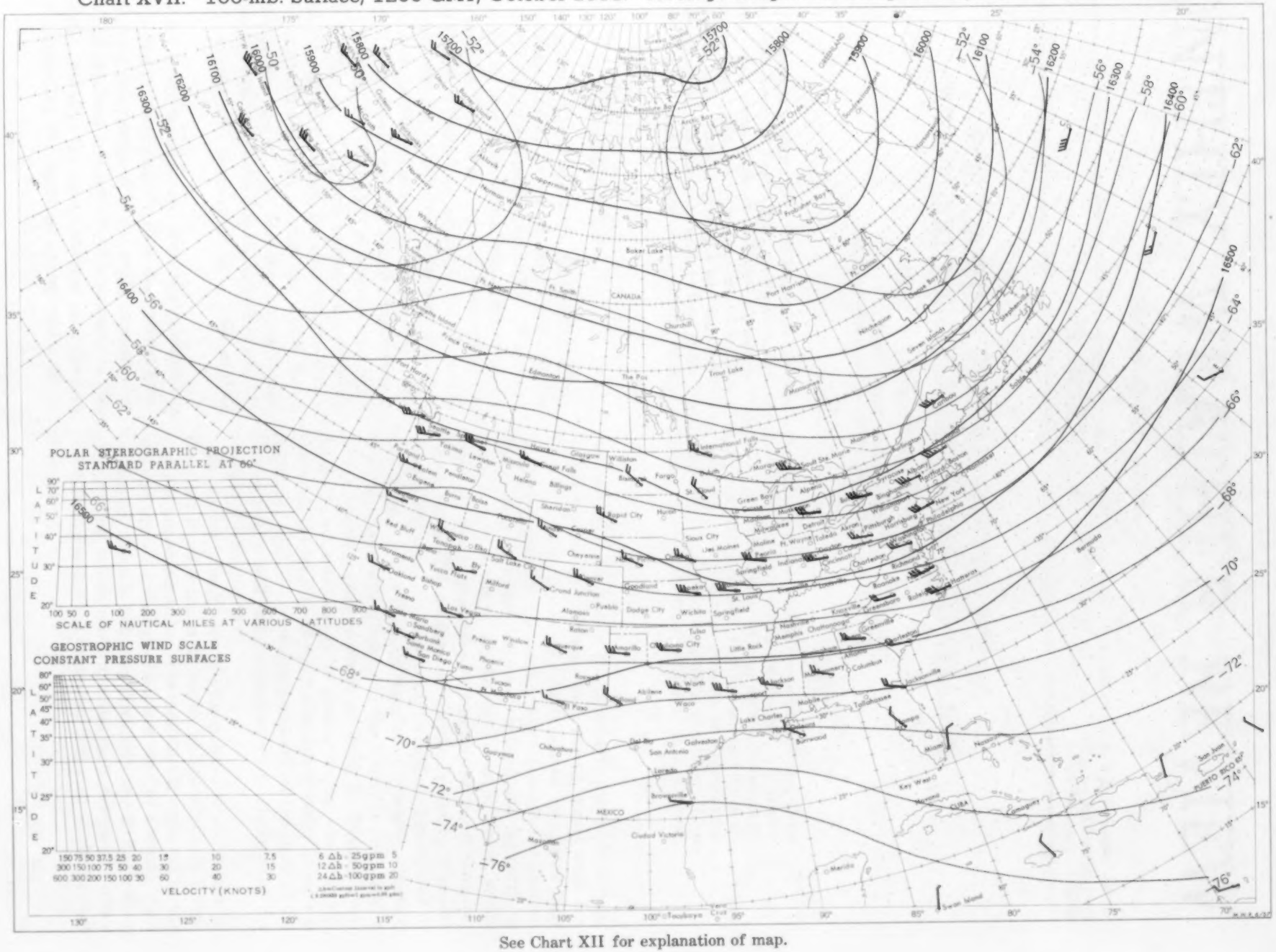
See Chart XII for explanation of map.

Chart XVI. 200-mb. Surface, 1200 GMT, October 1958. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.

Chart XVII. 100-mb. Surface, 1200 GMT, October 1958. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.